Draft User's Manual

FSEC 3.0

Florida Software for Enervironment Computation: V3.0

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Florida Solar Energy Center
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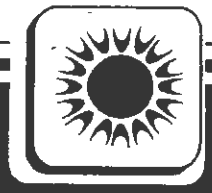

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User's Manual

FSEC 3.0

Florida Software for Enervironment Computation

Version 3.0

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ABSTRACT

FSEC 3.0 was developed to support research. It is a general-purpose software package especially designed to simulate complex building science problems. The program offers several unique features.

The major feature is its ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their corresponding boundary conditions may be either selected from libraries or defined by the user. The equations may be linear or nonlinear; spatially-lumped or spatially-distributed; steady-state or transient; ordinary or partial. The structure of the software also allows users to incorporate their own routines or programs. Thus, researchers may define their specific problem and incorporate it into a general software that provides the numerical framework for detailed computer simulation.

PREFACE

FSEC 3.0 was developed to support research. It is a general-purpose software package especially designed to simulate complex building science problems. The program offers several unique features.

The major feature is its ability to solve user-defined systems of governing equations. Up to 250 coupled differential equations and their corresponding boundary conditions may be either selected from libraries or defined by the user. The equations may be linear or nonlinear; spatially-lumped or spatially-distributed; steady-state or transient; ordinary or partial. The structure of the software also allows users to incorporate their own routines or programs. Thus, researchers may define their specific problem and incorporate it into a general software that provides the numerical framework for detailed computer simulation.

While the building science community constantly faces new problems and opportunities to improve building systems, adequate computational and simulation tools have not always been available. At nearly $200 billion per year, the U.S. building industry is economically analogous to the automotive industry, yet the emphasis on technology advancement has been vastly different. Advances in the automotive, aircraft and space industries would not have been possible without detailed simulation software. Such simulation packages are routinely used as research tools in these industries to evaluate and optimize the aerodynamic, structural, and thermodynamic behavior of complex systems. For these industries to design complex systems based solely on experimental research would be prohibitively time consuming and expensive.

Likewise, it is unlikely that significant technological advances in the building systems will be achieved without advanced simulation capabilities. Such tools allow researchers to study problems in detail using first principles. This obviates the need to make broad simplifying assumptions, enhances the reliability of the simulating results and allows the software to be used as a true research tool.

Most public domain software packages are developed to study specific problems and usually have a fairly rigid software structure. These software packages, if properly used, are excellent design tools for the general practitioner. For research purposes, however, the capabilities of the software and the objectives of the research are often incompatible. In the past, the researcher was left with only two options; either modify the software or develop new software.

Under the first option, the user became a slave to the software and had to struggle to overcome its limitations. Frequently, simplifying assumptions had to be made to meet research objectives. This usually led to a limited understanding of the underlying fundamental principles and sometimes led to errors that impeded the research. The second option, writing new software, is usually very costly and time consuming; few research projects can afford the time or expense.

The authors believe that FSEC 3.0 provides an additional option that satisfies a real need in building science research. The software allows many complex phenomena, heretofore difficult to study, to be defined by the user and examined in detail at a fundamental level. We do not believe that significant building science advancement will be achieved without such capabilities.

We are indebted to many who have helped along the way. The Gas Research Institute, the U.S. Department of Energy, Florida Power & Light Company and other organizations have either directly or indirectly contributed funding to the effort. In particular, Mr. Doug Kosar of the Gas Research Institute has enthusiastically supported our efforts to understand the behavior of moisture in buildings and has provided both encouragement and support for the software development. In addition, numerous students have spent long and arduous hours learning and executing the software in support of its development. It would be impossible to thank each one individually for his or her contribution. We are also fortunate enough to work at the Florida Solar Energy Center where an atmosphere that supports this type of effort is prevalent.

TABLE OF CONTENTS

	Page
List of Tables	xiii
List of Figures	xv
Introduction	xvii
Acronyms	xviii
Nomenclatures	xx
Greek Letters	xxii
Subscripts and Superscripts	xxv
Section 1 General Overview Florida Software for Enervironment Computation Version 3.0	
1.1 The Software	1-1
1.2 Building Science Applications	1-4
1.3 Overall Software Structure	1-5

Page

1.4 Hardware Requirements 1-8

1.5 Installation and Execution Procedures 1-8

Section 2 Main Program Input File

2.1 Master Contol 2-4

2.2 Node Generation 2-34

2.3 Element Generation 2-36

2.4 Material Property Specification 2-43

2.5 Boundary Condition Set Value Specification 2-51

2.6 Prescribed Value Specification 2-55

2.7 Boundary Condition Flag Generation 2-56

2.8 Wall Vorticity Distance Specification 2-58

2.9 Inter-Element Radiation Surface Generation 2-59

Page

2.10 Point Source Specification 2-62

Section 3 Buildings Program Input File

3.1 Master Control 3-2

3.2 Schedule Specification 3-10

3.3 Environmental Data Specification 3-11

3.4 Boundary Condition Modification 3-14

3.5 System Parameters 3-17

3.6 Zone Data 3-18

3.7 User Defined Mechanical Unit Performance Specification 3-27

3.8 User Defined Routines For The Buildings Program (Control Numbers) 3-30

3.9 User Defined Routines For The Leakage Source or Sink between Zones 3-37

3.10 Stratified Air Model of Attic Thermal Performance 3-39

		Page
3.11	Conduction Transfer Function Method	3-43
Section 4	**User Defined Routines, Equations, and Programs**	
4.1	User Defined Routines	4-1
4.2	User Defined or Modified Equations	4-8
Section 5	**Library Equations And Boundary Conditions**	
5.1	Domain and Boundary Definitions	5-1
5.2	Fluid Flow Equations in Primitive Variables	5-5
5.3	Vorticity and Stream Function Equations	5-7
5.4	Heat and Moisture Transfer Equations, Evaporation/Condensation Theory	5-11
5.5	Heat and Moisture Transfer Equations, Luikov's Theory	5-16
5.6	Contaminant Distribution Equation	5-18

Page

5.7 Turbulence Equations κ-ϵ Model 5-20

5.8 Multiphase Flow of Immiscible Fluids and Transport of Nonreactive Substances 5-21

5.9 Multiphase Radon Transport in Porous Media 5-31

Section 6 Example Simulations

6.1 Natural Convection in a Square Cavity Using (ω-ψ) 6-2

6.2 Natural Convection in a Square Cavity Using PFEM 6-7

6.3 Laminar Flow in a Duct System 6-11

6.4 Thermal Radiation in a Cavity 6-15

6.5 Formaldehyde Emission Rate of a Particle Board 6-22

6.6 Velocity Distribution in a Ventilated Room 6-25

6.7 Contaminant Distribution in a Ventilated Room 6-29

		Page
6.8	Validation of Evaporation and Condensation Theory	6-34
6.9	Radon Transport in Soil-Slab Composite	6-41
6.10	Heat Transfer in a Phase Change Material	6-47
6.11	Combined Heat and Mass Transfer in Building Using EMPD	6-50
6.12	Combined Heat and Mass Transfer in Building Using EVACON	6-60
Appendix A	Output and Input Data File Format	A-1
Appendix B	Input Summary	B-1
Glossary		G-1
Index		I-1
References		R-1

LIST OF TABLES

		Page
Table 1-1:	Building Simulation Modes	1-5
Table 1-2:	Files in the Software Package	1-9
Table 1-3:	File Extension and Their Content	1-11
Table 2-1:	Number of Gauss Points Required	2-6
Table 2-2:	Equation Library	2-17
Table 2-3:	Output Flags	2-29 2-30
Table 2-4:	Material Properties Required for Each Equation	2-49 2-50
Table 2-5:	Point Source Units and Definitions	2-63
Table 3-1:	Environmental Data File Format	3-12
Table 3-2:	Modifiable Variables for the Buildings Program	3-28
Table 3-3:	Variables Available to You in the Buildings Program	3-30
Table 4-1:	Modifiable Software Variables	4-2
Table 4-2:	Software Variables Used in the Definition of Modifiable Variables	4-4 4-5
Table 4-3:	Different Integration Types	4-14 4-15
Table 5-1:	Library Equations and Their Mathematical Formulations	5-2
Table 5-2:	Typical Boundary Conditions	5-4

		Page
Table 5-3:	Equations Combinations for Heat and Mass Transfer Simulations	5-12
Table 5-4:	Equation Combinations for Contaminant Distribution Simulations	5-18
Table 5-5:	List of Variables	5-26
Table 5-6:	Simulation Types and Corresponding Equations	5-30

LIST OF FIGURES

		Page
Figure 1-1:	Software Structure and Interfaces	1-6
Figure 2-1:	Coordinate System Used by the Software	2-3
Figure 2-2:	Element Types Supported by the Software	2-7
Figure 2-3:	Numbering Convention for Nodal Connectivity of Different Element Types	2-37
Figure 2-4:	Example of Node and Element Generation	2-39
Figure 2-5:	Example of Graded Mesh Generation	2-41
Figure 2-6:	Convention from Radiation Boundary Condition Generation	2-61
Figure 3-1:	Limits of Effective Penetration Depth Values for Various Vapor Diffusivities Evaluated at Different Ambient Excitations	3-15
Figure 4-1:	Conversion for Integration-Type Constants in CONPAR	4-13
Figure 4-2:	Schematic Definition of the Set of Equation	4-16
Figure 5-1:	Domain and Surface Definitions	5-3

INTRODUCTION

Florida Software for Enervironment (Energy and Environment) Computation version 3.0 (FSEC 3.0) is a general purpose software program designed to simulate science and engineering problems. The program solves existing library equations or equations developed for a specific problem. You may select the equation needed and adapt it to your needs. The program's main feature is its capability to interface with other software programs.

This manual offers these guidelines to help you use FSEC 3.0:

- General Overview
- Main Program Input File
- Buildings Program Input File
- User Defined Routines, Equations, and Programs
- Library Equations and Boundary Conditions.
- Appendix A: Output and Input Data File Format
- Appendix B: Input Summary

Information presented in this manual can be read sequentially or can be used as a reference guide.

These are the limitations of the software:

- Use only one type of element per simulation
- Use only one-dimensional elements for the wall structure in whole building simulations
- Requires extensive knowledge of numerical methods
- No detailed run-time warning or error messages
- No input file screening for contradictory or irrational data
- No parameter defaults built in
- No output post-processing provided
- Requires a basic knowledge of theoretical finite element analysis for your equations.

ACRONYMS

AFES	Algebraic Finite Element Statement
BNF	Backus-Naur Form
CPS	Computational Processor Segment
EMPD	Effective Moisture Penetration Depth
FSEC	Florida Software for Enervironment Computation
MSHGEN	Mesh Generation
PFEM	Penalty Finite Element Method
SI	Systeme International
SP	Spacing Factor
UDE	User Defined Equation
UDP	User Defined Program
UDR	User Defined Routines

NOMENCLATURE

A_T Isothermal moisture capacity based on water vapor density [m^3/kg]

B_ρ Thermo-gradient coefficient based on water vapor density [kg/kg.K]

C Contaminant concentration [kg/m^3]

C_M Isothermal moisture capacity used in Luikov's theory [kg/kg.°M]

C_o Reference contaminant concentration used in buoyancy calculation [kg/m^3]

C_p Specific heat [J/kg.K]

c_η^α Concentration of species η in phase α [kg/m^3]

D_a Molecular diffusivity of water vapor in air [m^2/s]

D_c Molecular diffusivity of contaminant in air [m^2/s]

D_v Water vapor diffusivity [m^2/s]

D_{ij}^α Diffusivity tensor of phase α [m^2/s]

F_{ij} Script-F factor [dimensionless]

Fs Thermal radiation view factor [dimensionless]

g Gravitational acceleration [m/s^2]

h Head ($P/\rho g + z$) [m]

h_M Convective mass transfer coefficient [m/s]

$h_{M.M}$ Convective mass transfer coefficient used in Luikov's theory [$kg/m^2.s.°M$]

NOMENCLATURE (continued)

h_T	Convective heat transfer coefficient [W/m^2.K]
k	Thermal conductivity [W/m.K]
k_M	Moisture conductivity used in Luikov's theory [kg/m.s.°M]
K_{ij}^{α}	$k_{ij}^{\alpha}\rho^{\alpha}g/\mu^{\alpha}$ [m/s]
k_{ij}^{α}	Intrinsic permeability of the material for phase α [m^2]
M	Mass transfer potential [°M]
m^{α}	Molar mass of the gas [?]
n	Normal vector [m]
nop	Number of phases [dimensionless]
nos	Number of species [dimensionless]
P	Total pressure [kg/m.s^2]
p	Pressure [kg/m.s^2]
P^{α}	Pressure for phase α [kg/m.s^2]
P_c^{α}	Capillary pressure at the interface of phases [kg/m.s^2]
P_o^{α}	Reference fluid pressure for phase α [kg/m.s^2]
Q	q dz [m/s]
q	Volumetric flow rate of fluid per unit volume of rock [1/s]
q"	Boundary flux for hydraulic head equation [m/s]
Q_C	Internal contaminant source/sink [kg/m^3]
Q_M	Internal moisture source/sink [kg/m^3]
Q_T	Internal heat source/sink [W/m^3]

NOMENCLATURE (continued)

q''_C	Imposed contaminant flux [kg/m^2.s]
q''_M	Imposed mass flux [kg/m^2.s]
q''_T	Imposed heat flux [W/m^2]
q^{α}_{η}	Boundary mass flux of contaminant η in phase α [kg/m^2.s]
Q^{α}	Sink/source for phase α [kg/m^3.s]
q^{α}	Boundary flux of phase α [m/s]
Q_{η}	Sink/source for specie η [kg/m^3.s]
R	Perfect gas constant [461.52 J/kg.K]
s_s	Specific storage [1/m]
S^{α}	Volumetric saturation for phase α (V^{α}/V_p) [dimensionless]
T	Temperature [K]
T_o	Reference temperature used in buoyancy calculation [K]
T_s	Radiation sink/source temperature [K]
T^{α}	Temperature for phase α [K]
u	Velocity [m/s] or displacement [m]
U_e	Equilibrium moisture content [kg/kg]
Uo	Reference velocity [m/s]
U^{α}	Darcy's velocity for phase α ($\phi S^{\alpha}u^{\alpha}$) [m/s]
V_P	Volume of pore [m^3]
V_T	Total volume [m^3]
V^{α}	Volume of phase α ($V_T\phi S^{\alpha}$) [m^3]

NOMENCLATURE (continued)

x	Cartesian coordinate direction [m]
z	Height above the datum [m]
Z^{α}	Compressibility factor for gaseous phase α [dimensionless]

GREEK LETTERS

α	Compressibility of porous matrix [$m.s^2/kg$]
α_s	Compressibility of solid grains [$m.s^2/kg$]
β_C	Contaminant expansion coefficient [m^3/kg]
β_L^{α}	Isothermal liquid compressibility [$m.s^2/kg$]
β_M	Moisture expansion coefficient [m^3/kg]
β_S	Isothermal solid grain compressibility [$m.s^2/kg$]
β_T	Thermal expansion coefficient [1/K]
Γ	Surface [dimensionless]
γ	Vapor diffusivity/total mass diffusivity [dimensionless]
Δn	Distance from wall [m]
δ	Thermo-gradient coefficient [1/K]
ϵ	Emissivity [dimensionless] or turbulent dissipation rate [m^2/s^3]
ϵ^{-}	Penalty parameter [dimensionless]
η	Index for the species [dimensionless]
κ	Turbulent kinetic energy [m^2/s^2]
Λ	Porosity [dimensionless]

GREEK LETTERS (continued)

λ	Heat of sorption [J/kg]
μ	Dynamic viscosity [kg/m.s]
μ_T	Turbulent eddy viscosity [kg/m.s]
μ^α	Viscosity of pure fluid in phase α [kg/m.s]
ρ	Density [kg/m^3]
ρ_b	Bulk density [kg/m^3]
ρ_v	Water vapor density [kg/m^3]
$\rho_{v,o}$	Reference water vapor density used in buoyancy calculation [kg/m^3]
ρ^α	Density of pure fluid in phase α [kg/m^3]
ρ_o^α	Reference pure fluid density in phase α [kg/m^3]
σ	Stefan-Boltzmann constant [W/m^2.K^4]
σ_C	Empirical constant used in the κ-ϵ turbulence model [dimensionless]
σ_M	Empirical constant used in the κ-ϵ turbulence model [dimensionless]
σ_T	Empirical constant used in the κ-ϵ turbulence model [dimensionless]
σ_ϵ	Empirical constant used in the κ-ϵ turbulence model [dimensionless]

GREEK LETTERS (continued)

σ_κ Empirical constant used in the κ-ϵ turbulence model [dimensionless]

τ Time [s]

τ_o Tortuosity [dimensionless]

Φ Dissipation function [$1/s^2$]

ϕ Relative humidity [dimensionless and $0 \leq \phi \leq 1$]

ϕ Porosity (V_p/V_T) [dimensionless]

ϕ_d Drainage porosity (part of porosity drained by gravity) [dimensionless]

ψ Stream function [m^2/s]

Ω Domain [dimensionless]

$\mathfrak{w}$ Vorticity [1/s]

ω_η^α Mass fraction of species η in phase α ($c_\eta^\alpha/\Sigma c_\eta^\alpha$)

SUBSCRIPTS AND SUPERSCRIPTS

e	Effective
G	Gas
i	Inflow
n	Wall node
n+1	Node away from wall
o	Outflow
R	Lump
S	Solid
v	Vapor
α	Ambient
*	Surface

SECTION 1

GENERAL OVERVIEW
FLORIDA SOFTWARE FOR ENERVIRONMENT COMPUTATION VERSION 3.0

This overview describes the software, program segments, hardware requirements, and installation and execution procedures of FSEC 3.0.

1.1 THE SOFTWARE

FSEC 3.0 has a variety of problem solving capabilities that can be used to study scientific and engineering problems at many levels of detail:

- Ability to create one-, two-, or three-dimensional simulations using distorted or undistorted elements
- Use automatic mesh generation with optimal bandwidth to minimize memory storage and computation time
- Select from a library of built-in governing equations or define additional equations
- Modify time steps, boundary conditions, numerical solution schemes, material properties, and other variables on a run-time basis
- Provide interfacing for routines and programs you define.

The speed which the program operates is dependent on your purpose. You set the pace at which the program will operate.

The software allows you to solve up to 250 coupled linear or nonlinear, spatially-distributed, steady-state, or transient partial differential equations simultaneously. The equations and boundary conditions can be selected from an equation library or defined by you.

These equations are available directly from the equation library and can be used through the input data file:

- X-momentum equations in primitive variables
- Y-momentum equations in primitive variables
- Z-momentum equations in primitive variables
- Stream-function equations
- Vorticity function equations
- U-velocity (Poisson's) equation for vorticity-stream function
- V-velocity (Poisson's) equation for vorticity-stream function
- Pressure equations in primitive variables
- Pressure equations for vorticity-stream function equations
- Energy equations in primitive variables
- Energy equations for vorticity-stream function
- Energy equations for Luikov's theory
- Vapor density equations in primitive variables
- Vapor density equations for vorticity- stream function equations
- Luikov's mass transfer potential equations
- Concentration equations in primitive variables
- Concentration equations for vorticity- stream function equations
- Turbulent kinetic energy equations in primitive variables
- Turbulent kinetic energy equations for vorticity-stream function equations
- Turbulent dissipation rate equations in primitive variables
- Turbulent dissipation rate equations for vorticity-stream function equations.
- Air pressure equation in the porous media
- Radon concentration equation in the porous media

You can modify any of the governing equations available in the library. (See Section 5)

The library equations can be solved using various boundary conditions. The boundary conditions are either selected from the boundary conditions library or defined by you.

These boundary conditions are in the library:

- Convection
- Radiation
- Imposed heat and mass flux
- Sublimation, fusion, or vaporization
- Insulation
- Impermeable
- Inflow
- Outflow
- No slip
- Injection
- Suction
- Free surface
- Wall turbulence
- Wall vorticity
- Prescribed.

Boundary conditions can be a function of time or any other field variable. You can modify the boundary conditions that are in the library. (See Section 5)

The software supports 10 different element types:

- One-dimensional linear line element (2 nodes)
- One-dimensional parabolic line element (3 nodes)
- One-dimensional cubic line element (4 nodes)
- One-dimensional quartic line element (5 nodes)
- Two-dimensional linear rectangular element (4 nodes)
- Two-dimensional parabolic rectangular element (8 nodes)
- Two-dimensional cubic rectangular element (12 nodes)
- Three-dimensional linear brick element (8 nodes)
- Three-dimensional parabolic brick element (20 nodes).

1.2 BUILDING SCIENCE APPLICATIONS

These are some of the building science applications the software is capable of simulating:

- Natural, forced, or mixed convection
- Combined heat and moisture transport
- Moisture and condensation and accumulation
- Vapor retarder placement
- Thermal bridging
- Airflow around buildings
- Contaminant disbursement
- Earth coupling
- Building load analysis
- Mechanical system performance
- Detailed materials, component or systems analysis
- Material property analysis and optimization
- System integration analysis
- Combined fluid flow and cavity radiation
- Radiant barrier system analysis.

The software allows you to perform combined heat and moisture transfer simulations at different levels of detail. For example, a building is composed of several solid and air interfaces. The solids may consist of the envelope, internal walls, or furniture, and air either indoor or outdoor. Spatially lumped or distributed equations may be used to define the characteristics of the solid and air domains. Based on this information, these simulation options are available:

- Distributed heat and moisture transfer calculations for solid and air domains
- Distributed heat and moisture transfer calculations for solid domains exposed to user define boundary conditions
- Distributed heat and moisture calculations for solids and lumped heat and moisture calculations for air
- Distributed heat transfer calculations for solids, lumped moisture transfer calculations for solids, and lumped heat and moisture calculations for air.

Table 1-1 provides a summary of the allowable building simulation modes.

Table 1-1: Building Simulation Modes

Model Number	Zone Air		Solid Heat Transfer		Solid Mass Transfer	
	L	D	L	D	L	D
1		X		X		
2		X		X		X
3*				X		
4#				X	X	
5				X		X

L Spatially Lumped
D Spatially Distributed
* Current Public Domain Building Energy Analysis Software
# TARP, TRNSYS (FSEC Versions)

1.3 OVERALL SOFTWARE STRUCTURE

Many of the capabilities of FSEC 3.0 are derived from the software structure itself. The general architecture of the software is given in Figure 1-1. The Computational Processor Segment (CPS) is the heart of the software. The CPS performs these operations:

- Computes the capacitance, stiffness, and Jacobian matrices and force vectors on an elemental basis, using numerical volume and surface integrations
- Assembles the element matrices and force vectors
- Solves the resulting linear or nonlinear algebraic equations.

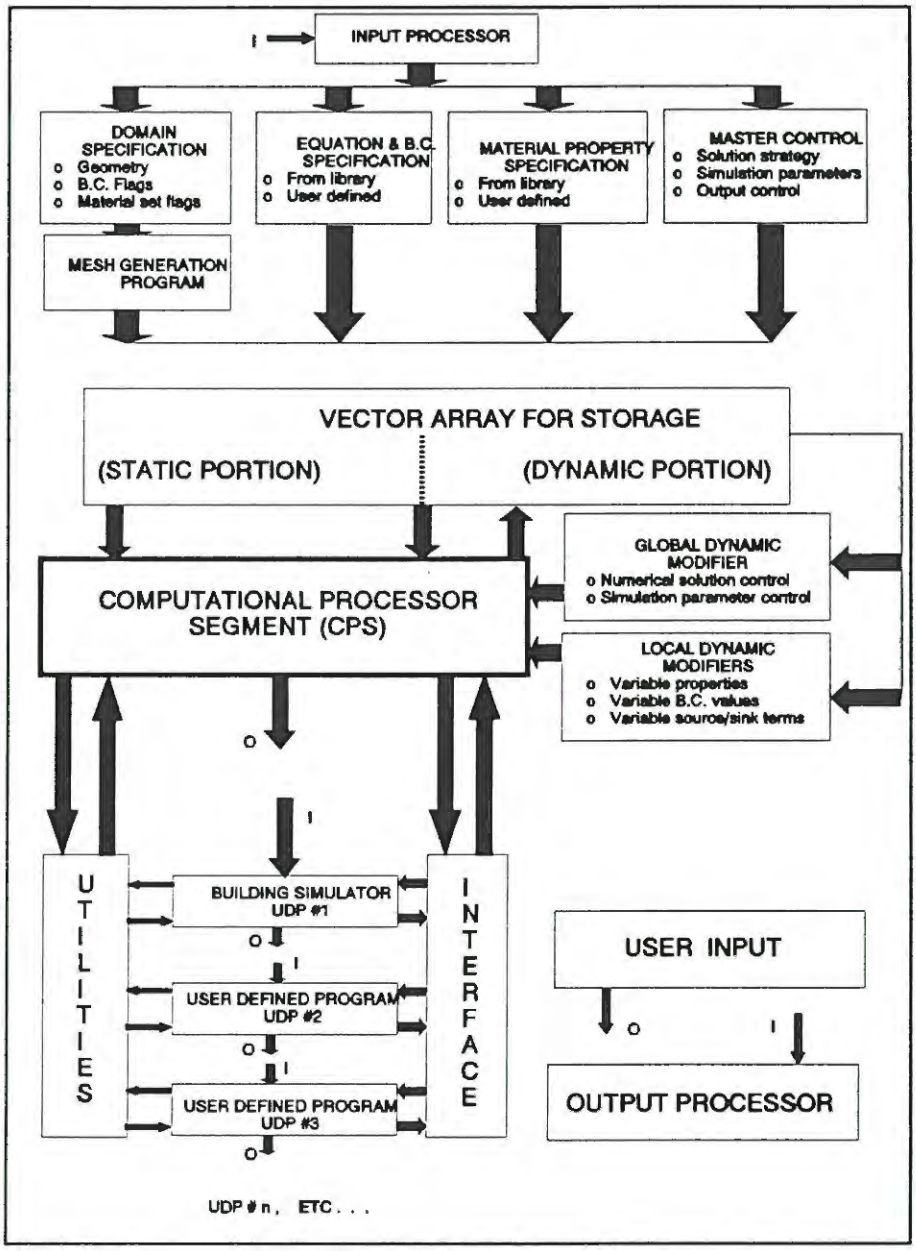

Figure 1-1: Software Structure and Interfaces

This portion of the software can be independently executed without interfacing with User Defined Programs (UDP). The building simulator is connected to the CPS through a common interface. Similarly, other UDP's can be connected to the CPS through this interface. UDP's are stand-alone software elements; they may receive information from the CPS and return information to the CPS. For example, the building simulator receives surface temperatures and moisture conditions from the CPS and returns the zone air temperatures and moisture conditions to the CPS through the interface.

During each time step, certain parameters can be modified through User Defined Routines (UDR). These modifications can be local or global. (See Figure 1-1). Local modifications are performed on an elemental level, such as field variable dependent material properties or boundary conditions. Global modifications are performed at the beginning of a time step. Examples of global modifications include time dependent material properties or boundary conditions, variable time-step simulations, and numerical solution schemes.

The software uses a single vector array to store all information. The dimension of the array is at the maximum capacity of the hardware being used. The array is a priori partitioned to separate the different data segments. This vector is conceptually divided into static and dynamic portions. The static portion contains the data that is stationary during execution, such as nodal coordinates, nodal connectivity, and material and boundary condition flags. The dynamic portion contains the data that is calculated during execution, such as global capacitance and stiffness matrices, force vectors, and nodal unknowns at various iterations.

Advantages of vector array storage:

- Reduces the storage requirement of the coefficient matrix
- Provides flexible storage based on the element type and the number of nodes
- Allows access to software variables for UDR's and UDP's.

1.4 HARDWARE REQUIREMENTS

The software is written using standard FORTRAN 77 and it is developed on VAX 11/750. Currently, the software is applicable only for VAX/VMS series.

1.5 INSTALLATION AND EXECUTION PROCEDURES

The software installation and execution procedures are provided for you in Table 1-2. The software package consists of thirteen files. The main program and subroutines CONPAR, INVOKE, MODELS, and VRPROP are included. The source code can be edited with equations or routines you define.

Table 1-2: Files in the Software Package

FILE NAME	TYPE	CONTENT
FSEC.OBJ	Object Code	Main Program
BILD.FOR	Source Code	Program segment that includes the subroutines used in building simulations
USER.FOR	Source Code	Program segment that includes the subroutines used in defined routines, programs, and equations
EXM1.DAT	Data File	Example Data File (duct flow)
EXM1.LOG	Data File	Output Data File for EXM1.DAT
EXM2.DAT	Data File	Example Data File (building)
ZONE.DAT	Data File	Zone Data File for EXM2.DAT
AMBI.DAT	Data File	Ambient Data File for ZONE.DAT
EXM2.LOG	Data File	Output Data File for EXM2.DAT
FOR031.DAT	Data File	Output Data File for ZONE.DAT
FOR032.DAT	Data File	Output Data File for ZONE.DAT
FOR033.DAT	Data File	Output Data File for ZONE.DAT
FOR034.DAT	Data File	Output Data File for ZONE.DAT

For installation, follow these steps:

1. Create a directory
2. Copy the files to the created directory
3. Compile BILD.FOR and USER.FOR
4. Create BILD.OBJ and USER.OBJ
5. Link FSEC, BILD, and USER to create FSEC.EXE

Note: USER.FOR is for programs you define.

For execution, follow these steps:

1. Define FSEC

```
FSEC :== "$<your disk>:[<directory name>]FSEC"
```

2. Type

```
FSEC <enter file name with an extension>
```

To execute the example file, type FSEC EXMP.DAT.

Note: The input file must always contain a file name, period, and an extension.

After successful execution, the information is written in an output data file. The output data file name is always the same as the input data file name, except the extension DAT is replaced by LOG. The program automatically changes the extension. Table 1-3 provides the extensions used in the output files.

Table 1-3: File Extensions and Their Content

File Extension	Data File Content
<FL>.CTL	Interactive control fIle
<FL>.DAT	Input data file
<FL>.FLX	Output data file that contains the fluxes to be used in vector plots
<FL>.LOG	Hardback output data file
<FL>.MSH	Output data file to plot the mesh
<FL>.RES	Output data file that contains the nodal unknowns to be used in contour plots
<FL>.VIW	Output data file that contains the thermal radiation view factors
<FL>.VOR	Output data file that contains the wall vorticity data
Note: <FL> indicates the original input file name without the extension. The formats used in the output files are given in Appendix A.	

SECTION 2

MAIN PROGRAM INPUT FILE

INTRODUCTION

This section contains guidelines to prepare the input file for the main FSEC 3.0 program. The section is divided into ten subsections which list the input variables and describe line by line the way these variables must be entered.

INPUT DIRECTIONS

Follow these directions to ensure proper input of data:

- Identify each input line using this line format:

  Line number: **variable 1, variable 2,...variable n**

- Identify variables that begin with I, J, K, L, M, N, as integers. All others variables are real numbers.

- Separate input data either by commas or spaces.

- Repeat lines with vertical ellipses, three dots aligned on top of each other, as many times as necessary, depending on the problem you are solving.

  Example:

  Line 8: **NEQ, VO, RLX, ERROR, THETA**

  .
  .
  .

Enter this data:

1	0.0	0.5	0.8	0.4
2	00.	0.6	0.8	0.5
3	0.0	0.6	0.8	0.5
10	300.0	0.9	0.1	0.9

- Use the coordinate system adopted by the software. (See Figure 2-1)
- Provide any engineering units you wish, but always use the same type of unit or your solutions will not be accurate.

Note: Always enter the unit of time in hours unless the directions specify a different unit.

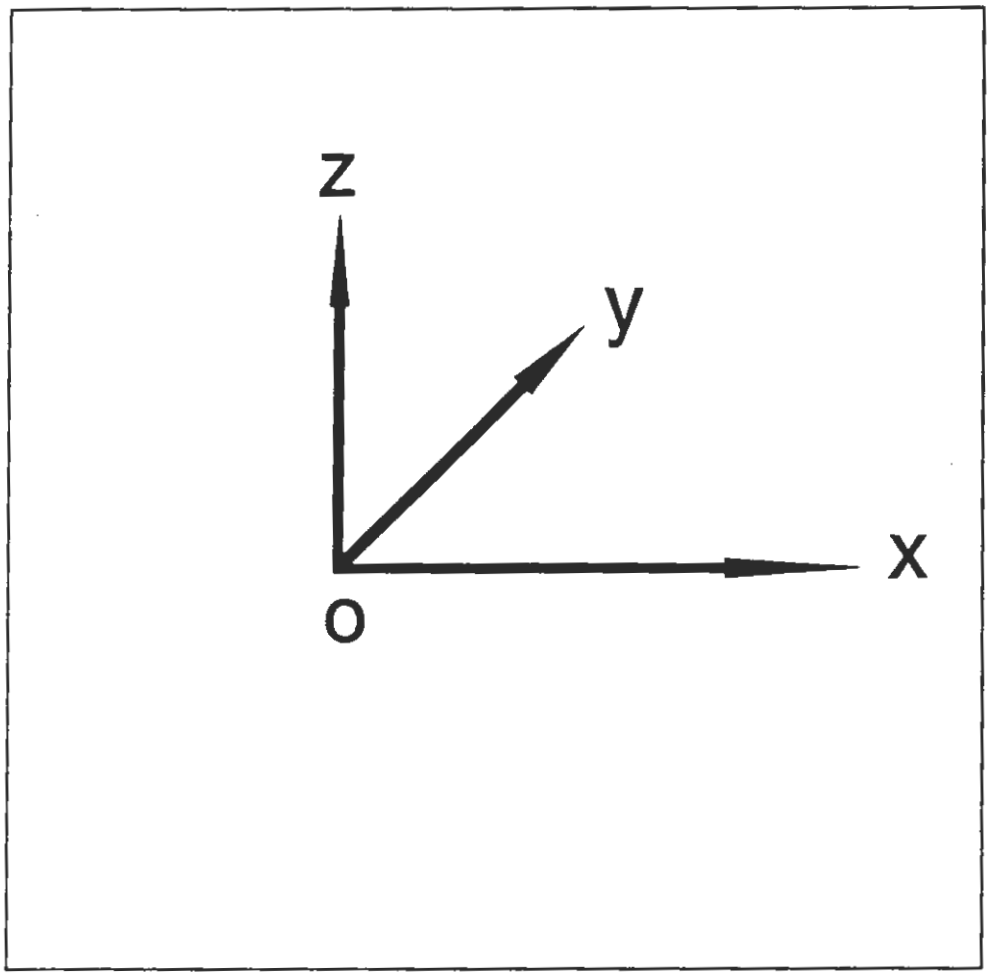

Figure 2-1: Cartesian Coordinate System Using Right-hand Rule.

2.1 MASTER CONTROL

This subsection contains information to enter the master control data required by the software.

Line 1: TITLE

TITLE	Alphanumerical problem title that is a maximum 80 characters long. This title line is imported in appropriate places such as hardback copies and output files to help distinguish among different simulations. This input is optional and may be left blank.

Line 2: NOFNOD, NOFELE, NOFMAT, NOFBCO, NOFPRS, NETYPE

NOFNOD	Total number of nodes used in the simulation
NOFELE	Total number of elements used in the simulation
NOFMAT	Total number of materials (material sets) specified in Subsection 2.4. Each material specified in Subsection 2.4 must have a unique material (material set) number that is an integer number greater than 0 and less than or equal to NOFMAT. Not all of the material properties specified in Subsection 2.4 are used for each simulation.
NOFBCO	Total number of boundary conditions (boundary condition sets) specified in Subsection 2.5. Each boundary condition specified in Subsection 2.5 must have a unique boundary condition (boundary condition set) number that is an integer number greater than 0 and less than NOFBCO. All the boundary condition set values specified in Subsection 1.5 are not necessarily used for each simulation.

NOFPRS — Total number of prescribed boundary conditions specified in Subsection 2.6. Not all of the prescribed boundary condition values specified in Subsection 2.6 are used for each simulation.

NETYPE — Element type used in the simulation. Element type flags. (See Figure 2-2) Use only one type of element during simulation so the mesh consists of the same type of element.

The element type used in the simulation affects the accuracy and convergence of the solution and required CPU time.

For the same number of nodes, higher order elements generally give more accurate results.

Depending on the element and simulation type, the proper number of Gauss points, NOFGAU as defined in Line 5, must be used. (See Table 2-1)

Table 2-1: Number of Gauss Points Required

NETYPE	No Thermal Radiation	With Thermal Radiation
1	2	3
2	3	5
3	4	6
4	5	6
5	2	3
6	3	5
7	3	5
8	4	6
9	2	3
10	3	5

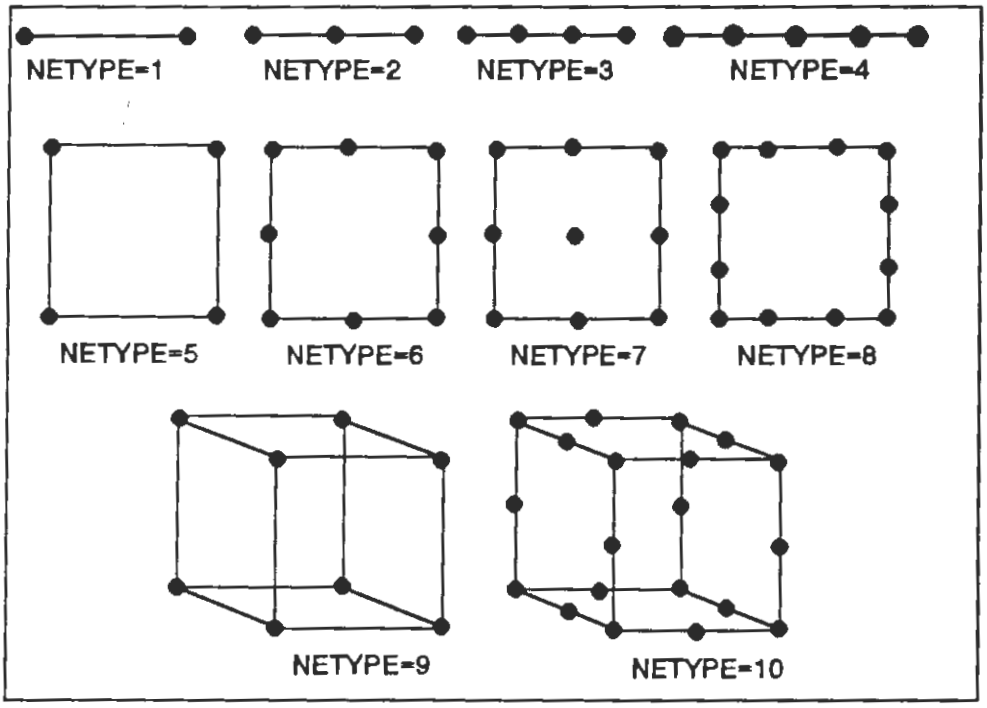

Figure 2-2: Element Types Supported by the Software

Line 3: **MODE, ILMP, TINT, TSTP, TFIN**

MODE Simulation mode

MODE Enter 0 for steady-state.

MODE Enter +1 for transient (time dependent problems).

The general algebraic statement for transient simulation can be written as:

$$(C+\Theta\ K\Delta\tau)\ a^{\tau+\Delta\tau} = \left[C-(1-\Theta)\ K\Delta\tau\right] a^{\tau} + (1-\Theta)f^{\tau}\ \Delta\tau + \Theta f^{\tau+\Delta\tau}\Delta\tau \qquad \textbf{(2-1)}$$

If you enter 1 for the Mode:

Matrix $(C+\Theta K\Delta\tau)$ and vector $\Theta\Delta\tau f^{\tau+\Delta\tau}$ are evaluated at $a^{\tau+\Delta\tau}$

Matrix $C-(1-\Theta)K\Delta\tau$ and vector $(1-\Theta)\Delta\tau f^{\tau}$ are evaluated at a^{τ}

If you enter -1 for the Mode:

Matrix $(C+\Theta K\Delta\tau)$ and vector $\Theta\Delta\tau f^{\tau+\Delta\tau}$ are evaluated at $a^{\tau+\Delta\tau}$

Matrix $C-(1-\Theta)K\Delta\tau$ and vector $(1-\Theta)\Delta\tau f^{\tau}$ are evaluated at $a^{\tau+\Delta\tau}$

ILMP Capacitance matrix type

ILMP Enter 0 for consistent capacitance matrix.

ILMP Enter 1 for lumped capacitance matrix.

Note: For transient problems with oscillations in the solution (especially early in the simulation) select a lumped capacitance matrix because it will filter these oscillations to a certain extent.

TINT Simulation start time is always in hours and is not necessarily equal to 0

TSTP Simulation time step is always in hours

TFIN Simulation stop time is always in hours

Note: You may set ILMP, TINT, TSTP, and TFIN to zero for steady-state problems.

Line 4: NDOF, NEWTON, MAXITR

NDOF Degrees of freedom

NDOF Enter 1 or NOFEQN (number of equations).

The definition of degrees of freedom used in this manual is different than the definition commonly used in structural problems. In this manual, NDOF defines how many equations are solved simultaneously. If three equations are solved and NDOF is set to 1, each equation is assembled and solved successively. However, if NDOF is set to 3, all the equations are assembled and solved simultaneously. Set the value of NDOF either to 1 or to the number of equations that are simulated. If only one equation is solved, NDOF can only be set to 1.

Note: Use an iterative procedure if more than one linear equation is solved and NDOF is set to 1. The equations are solved one by one until a specified convergence tolerance is achieved. This procedure requires more CPU time, but less storage space is allocated for NDOF 1. If you use the penalty finite element method to solve the fluid flow equations in primitive variables, set NDOF to NOFEQN.

NEWTON Iteration type

NEWTON Enter 0 for direct iteration.

NEWTON Enter 1 for Newton-Raphson iteration.

NEWTON Enter 2 for Quasi Newton-Raphson.

Note: You may use direct iteration for both linear and nonlinear problems, but Newton-Raphson iteration must be used with nonlinear problems. If you choose the Newton-Raphson method, NDOF (degrees of freedom) specified in Line 4 must be equal to NOFEQN (number of equations to be solved) specified in Line 7. Using the Newton-Raphson method, the Jacobian matrix is automatically constructed using numerical differentiation. Construction of the Jacobian matrix requires a considerable amount of CPU time. It is not necessary to evaluate the Jacobian matrix at each iteration. (See Line 11, CON(30))

MAXITR Maximum number of iterations. For linear problems using NDOF=NOFEQN set this value to 0, and set the relaxation coefficients used in Line 7 of this Subsection to 1 to prevent unnecessary iterations from being performed by the software.

Line 5: **SCALE, NDISTR, NOFGAU, NVORTY**

SCALE — Scaling factor applied to x-, y-, and z-coordinates. The scaling factor multiplies all nodal coordinates and wall-vorticity distances (specified in Subsection 2.8) by this factor.

NDISTR — Element distortion flag

NDISTR — Enter 0 to indicate that no distorted elements are used.

NDISTR — Enter 1 to indicate that distorted elements are used.

This parameter indicates if you have generated any distorted elements. Here, a priority indication saves CPU time if all elements used are undistorted.

Distorted elements:

- One-dimensional elements with unequal distances among their nodes or with nodes misaligned on a line.
- Two and three dimensional elements with edge angles other than 90°
- Mid-side nodes that are not equally spaced and are misaligned on a line.

Note: The software requires more CPU time if you use distorted elements.

NOFGAU — Number of Gauss points to be used in one direction. The number of Gauss points used is a function of the element type used. Table 2-1 gives the minimum number of Gauss points used for the element types that are supported.

NVORTY Wall-vorticity equation type. Choose the two possible equations for wall-vorticity by the entering the appropriate flag:

NVORTY 1 $\omega^n = 2\,(\psi^n - \psi^{n+1})/\Delta n^2$

NVORTY 2 $\omega^n = -0.5\,\psi^{n+1} + 3\,(\psi^n - \psi^{n+1})/\Delta n^2$

Note: In the NVORTY equations, n and n+1 give the conditions at the wall and Δn distance away from the wall, respectively. If you do not solve the vorticity equation, ignore this parameter and set the value to 0.

Line 6: **MODSTR, NFGCTF**

MODSTR Flag for stress calculation type

Note: MODSTR is not currently used. Enter 0.

NFGCTF Flag for conduction transfer function (CTF)

NFGCTF Enter 0 for FEM calculation

NFGCTF Enter 1 for CTF calculation (Equation 10 only)

Line 7: **NOFEQN, (NUMEQU(I), I=I,NOFEQN)**

NOFEQN Total number of equations to be solved

NUMEQU Equation number from Table 2-2

Note: A negative equation number indicates that you must enter the nodal unknowns for that equation through the USEGET file. (See Line 26) The equations indicated by a minus number will not be solved, but the nodal unknowns pertaining to this equation are used as input in other equations requiring them. NOFEQN also includes the equations that are denoted by negative numbers. For the equations denoted by negative numbers, no further data is required such as boundary set specifications.

Line 8: **NEQ, VO, RLX, ERROR, THETA**

.
.
.

NEQ Equation number from Table 2-2

VO Initial condition. Sets all the nodal unknowns to this value. If you are using different initial conditions for different nodes you must use the INIGET file (See

Line 25), and the value of VO must be set to -32767.

Note: Your choice of initial values is important for nonlinear problems because proper specification of initial values strongly effects the convergence and the number of iterations required for convergence.

RLX — Relaxation parameter $0 < RLX \leq 1$. Use this parameter for nonlinear problems or multiple equation simulations using the option of NDOF 1 in Subsection 2.1, Line 4. For highly nonlinear problems under relaxation, RLX < 0.5 enhances convergence. For linear problems or multiple equation simulations using the option of NDOF = NOFEQN, set this value to 1 to prevent unnecessary iterations. The current values are modified according to this equation:

$$a^n = (1\text{-}RLX)\, a^{n-1} + RLX\, a^n$$

CAUTION: The choice of this parameter is **crucial** to the convergence. If you enter the wrong selection, the solution may not converge. Since this parameter varies from simulation to simulation, be specific when selecting this value.

ERROR — Percentage of error tolerance. In this version of the software, error tolerance is defined as the percentage of error between the two succeeding iterations. Convergence is assumed if the percentage of difference between the two successive iterations for each node is smaller than the specified error tolerance. The error tolerance (ϵ) is defined as:

$$\epsilon \geq \left| \frac{\|[a^{i}]^T\ [a^{i}]\| - \|[a^{i+1}]^T\ [a^{i+1}]\|}{\|[a^{i+1}]^T\ [a^{i+1}]\|} \right| 100 \qquad \textbf{(2-2)}$$

In Equation 2-2, a^i and a^{i+1} are the nodal unknowns at the i-th and i+1-th iterations, respectively.

Note: Enter this line for each equation that is represented with a positive equation number in Subsection 2.1, Line 7.

THETA — Time integration constant $0 \leq$ THETA ≤ 1

THETA	Enter 0.000 for Forward difference scheme (Euler).
THETA	Enter 0.333 for Galerkin.
THETA	Enter 0.500 for Central difference scheme (Crank-Nicolson).
THETA	Enter 0.666 for Galerkin.
THETA	Enter 1.000 for Backward difference scheme.

Note: The selection of this number is completely problem dependent, and can be any value between 0 and 1. The recommended value is 0.5 or higher. If using a THETA value of 0 and a lumped capacitance matrix, the problem is fully explicit. The proper selection of this number is a strong function of the time step used.

Table 2-2: Equation Library

No	Symbol	Equation Name
1	u_1	X_1-momentum equation in primitive variables [m/s]1
2	u_2	X_2-momentum equation in primitive variables [m/s]
3	u_3	X_3-momentum equation in primitive variables [m/s]
4	ψ	Stream function equation [m^2/s]
5	ω	Vorticity function equation [1/s]
6	u_1	X_1-velocity, Poisson's, equation with ω-ψ [m/s]
7	u_2	X_2-velocity, Poisson's, equation with ω-ψ [m/s]
8	P	Pressure equation in primitive variables [$kg/m.s^2$]
9	P	Pressure equation with ω-ψ [$kg/m.s^2$]
10	T	Energy equation in primitive variables [K]
11	T	Energy equation with ω-ψ [K]
12	T	Energy equation used in Luikov's equations [K]
13	ρ_v	Vapor density equation in primitive variables [kg/m^3]
14	ρ_v	Vapor density equation with ω-ψ [kg/m^3]
15	M	Luikov's mass transfer potential equation [°M]
16	C	Concentration equation in primitive variables [kg/m^3]
17	C	Concentration equation with ω-ψ [kg/m^3]
18	κ	Turbulent kinetic energy equation in primitive variables [m^2/s^2]
19	κ	Turbulent kinetic energy equation with ω-ψ [m^2/s^2]
20	ϵ	Dissipation rate of turbulence equation in primitive variables [m^2/s^3]
21	ϵ	Dissipation rate of turbulence equation with ω-ψ [m^2/s^3]
22		Not used
23		Not used
24		Not used
25	P	Air pressure in the porous media (Pa)
26	C_a	Radon concentration in the porous media (Bq/m^3)

Use Lines 9 through 13 to define constant variables (variables that remain constant throughout the simulation). These lines define equations, boundary conditions, and functions specified in Subroutine VRPROP. The constant array CON(I) defined between Lines 9 and 13 is also passed to your defined problems. You may use the lines marked **Not used** to specify the constants needed in your problems.

Line 9: **CON(I),I=01.10)**

CON(01) Acceleration due to gravity in the x-direction, g_x. Refer to the coordinate system shown in Figure 2-1 to determine the sign and magnitude. If buoyancy is not simulated, set this value to 0 [m/s^2]

CON(02) Acceleration due to gravity in the y-direction, g_y. Refer to the coordinate system shown in Figure 2-1 to determine the sign and magnitude. If buoyancy is not simulated, set this value to 0 [m/s^2]

CON(03) Acceleration due to gravity in the z-direction, g_z. Refer to the coordinate system shown in Figure 2-1 to determine the sign and magnitude. If buoyancy is not simulated, set this value to 0 [m/s^2]

CON(04) Reference temperature, T_o used in the buoyancy calculations. If using vorticity and stream function formulations or if buoyancy is not simulated, set this value to 0 [K]

CON(05) Reference water vapor density, $\rho_{v,o}$ used in the buoyancy calculations. If you use vorticity and stream function formulations, or if buoyancy is not simulated, set this value to 0 [kg/m^3]

CON(06) Reference contaminant concentration, C_o used in the buoyancy calculations. If you use vorticity and stream function formulations, or if buoyancy is not simulated, set this value to 0 [kg/m^3]

CON(07) Not used
CON(08) Not used
CON(09) Not used
CON(10) Not used

Line 10: **(CON(I),I=11,20**

CON(11) Empirical constant used in κ-ϵ model, σ_C. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(12) Empirical constant used in κ-ϵ model, σ_M. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(13) Empirical constant used in κ-ϵ model, σ_T. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(14) Empirical constant used in κ-ϵ model, σ_ϵ. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(15) Empirical constant used in κ-ϵ model, σ_κ. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(16) Empirical constant used in κ-ϵ model, C_μ. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(17) Empirical constant used in κ-ϵ model, C_1. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(18) Empirical constant used in κ-ϵ model, C_2. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(19) Empirical constant used in κ-ϵ model, C_3. If κ-ϵ model is not simulated this value is not required and can be set to 0 [dimensionless].

CON(20) Not used

Line 11: **(CON(I), I=21,30)**

CON(21) Stefan-Boltzmann constant, σ [5.67×10^{-8} W/m^2.K^4]

CON(22) Barometric pressure, P_b [101325.0 k/m.s^2]

CON(23) Ideal gas constant, R_v [461.52 J/kg.K]

CON(24) Not used

CON(25) Extremely large number. Use the extremely large number to incorporate the prescribed (imposed) nodal unknown values into the solution scheme. If the n-th unknown's value is prescribed then the n-th diagonal location of the stiffness matrix is replaced by the product of the extremely large number and the prescribed value. If the value of the extremely large number is set to 0 use a default value of 1.0E+20.

CON(26) Penalty parameter, ϵ^-, is used in the penalty finite element formulations for the solution of flow equations in primitive variables. Select the penalty parameter depending on your computer accuracy. Typically, the penalty parameter is selected according to this equation:

$$\epsilon^- = \xi/\lambda$$

Where λ depends on your computer's accuracy, an appropriate choice for $\epsilon^- = \xi/\lambda$ is 1.0E-6. For slow viscous flows where the diffusion term dominates the problem set ξ to the molecular viscosity (μ). For high Reynolds (Re) number flows where the convective terms dominate the viscous terms, select ξ as:

$$\xi = \max(\mu, \mu * Re)$$

CON(27) $\Delta a_T^{\pm}$ used in the construction of Jacobian matrix.

CON(28) $\Delta a_\rho^{\pm}$ used in the construction of Jacobian matrix.

CON(29) Not used

CON(30) Number of times that the Jacobian matrix will be calculated.

Line 12: **(CON(I), I=31,40)**

CON(31)	Radon distribution coefficient (water/air) from Henry's law, k [0.26 at 20°C]
CON(32)	Dynamic viscosity of air, μ [1.8×10^{-5} Pa.s]
CON(33)	^{222}Rn decay constant, λ [2.1×10^{-6} 1/s]
CON(34)	Not used
CON(35)	Not used
CON(36)	Not used
CON(37)	Not used
CON(38)	Not used
CON(39)	Not used
CON(40)	Not used

Line 13: **(CON(I), I=41,50**

CON(41)	Not used
CON(42)	Not used
CON(43)	Not used
CON(44)	Not used
CON(45)	Not used
CON(46)	Not used
CON(47)	Not used
CON(48)	Not used
CON(49)	Not used
CON(50)	Not used

Lines 14 through 18 define global variables. These variables are part of the problem and may depend on the field variables and strategy you use. Use these variables in Subroutine VRPROP in the definition of equations, boundary conditions, or functions you defined in Subroutine VRPROP.

For each global variable, enter a relation between the global variable and variables of the governing equation(s) that is simulated. In the simulations, both the global variable and the field variable convergence are checked.

The global variables are iteratively calculated at the beginning and end of a complete iteration loop. Their values remain constant throughout the calculation of elemental matrices and vectors such as stiffness, capacitance, and mass matrices and force vector. The global variables are printed at the end of each iteration and/or at the end of convergence depending on the options you have entered.

Subroutine VRPROP defines the scheme used to specify the global variables. In the input file, use a negative number that is less than -1000 to define the global variable. If you assign a global variable to a number -(1000+N), you are required to enter the data in Subroutine VRPROP with a statement labeled N. (See Section 4, Subsection 4.1)

Line 14: **(VRG(I), I+01,10)**

VRG(01)	Not used
VRG(02)	Not used
VRG(03)	Not used
VRG(04)	Not used
VRG(05)	Not used
VRG(06)	Not used
VRG(07)	Not used
VRG(08)	Not used
VRG(09)	Not used
VRG(10)	Not used

Line 15: **(VRG(I), I=11,20)**

VRG(11)	Not used
VRG(12)	Not used
VRG(13)	Not used
VRG(14)	Not used
VRG(15)	Not used
VRG(16)	Not used
VRG(17)	Not used
VRG(18)	Not used
VRG(19)	Not used
VRG(20)	Not used

Line 16: **(VRG(I), I=21,30)**

VRG(21)	Not used
VRG(22)	Not used
VRG(23)	Not used
VRG(24)	Not used
VRG(25)	Not used
VRG(26)	Not used
VRG(27)	Not used
VRG(28)	Not used
VRG(29)	Not used
VRG(30)	Not used

Line 17: **(VRG(I), I=31,40**

VRG(31)	Not used
VRG(32)	Not used
VRG(33)	Not used
VRG(34)	Not used
VRG(35)	Not used
VRG(36)	Not used
VRG(37)	Not used
VRG(38)	Not used
VRG(39)	Not used
VRG(40)	Not used

Line 18: **(VRG(I), I=41,50)**

VRG(41)	Not used
VRG(42)	Not used
VRG(43)	Not used
VRG(44)	Not used
VRG(45)	Not used
VRG(46)	Not used
VRG(47)	Not used
VRG(48)	Not used
VRG(49)	Not used
VRG(50)	Not used

Lines 19 through 23 define local variables. These variables are part of the problem and depend on the field variables and control scheme you choose. Use these variables in the definition of equations, boundary conditions, or any function you specified in Subroutine VRPROP.

For each local variable, you are required to enter an equation between the local variable and the variables of the governing equation(s) that is simulated. In the simulations, both the field variable convergence and the local variable convergence are checked.

The local variables are iteratively calculated within each iteration loop for each element. Their values change throughout the calculation of elemental matrices and vectors such as stiffness, capacitance and mass matrices, and force vector. The local variables are printed at the end of each iteration and/or at the end of convergence depending on the options you provide.

Subroutine VRPROP defines the strategy used to specify the local variables. Use a negative number that is less than -1000 in the input file to define the local variable. If the value of a local variable is assigned to a number -(1000+N), you are required to enter the data in Subroutine VRPROP with a statement labeled N. (See Section 4, Subsection 4.1)

Line 19: **(VRL(I), I=01,10)**

VRL(01)	Not used
VRL(02)	Not used
VRL(03)	Not used
VRL(04)	Not used
VRL(05)	Not used
VRL(06)	Not used
VRL(07)	Not used
VRL(08)	Not used
VRL(09)	Not used
VRL(10)	Not used

Line 20: **VRL(I), I=11,20)**

VRL(11)	Not used
VRL(12)	Not used
VRL(13)	Not used
VRL(14)	Not used
VRL(15)	Not used
VRL(16)	Not used
VRL(17)	Not used
VRL(18)	Not used
VRL(19)	Not used
VRL(20)	Not used

Line 21: **(VRL(I), I=21,30)**

VRL(21)	Not used
VRL(22)	Not used
VRL(23)	Not used
VRL(24)	Not used
VRL(25)	Not used
VRL(26)	Not used
VRL(27)	Not used
VRL(28)	Not used
VRL(29)	Not used
VRL(30)	Not used

Line 22: **(VRL(I), I=31.40)**

VRL(31)	Not used
VRL(32)	Not used
VRL(33)	Not used
VRL(34)	Not used
VRL(35)	Not used
VRL(36)	Not used
VRL(37)	Not used
VRL(38)	Not used
VRL(39)	Not used
VRL(40)	Not used

Line 23: **(VRL(I), I=41,50)**

VRL(41)	Not used
VRL(42)	Not used
VRL(43)	Not used
VRL(44)	Not used
VRL(45)	Not used
VRL(46)	Not used
VRL(47)	Not used
VRL(48)	Not used
VRL(49)	Not used
VRL(50)	Not used

Note: In Line 24, you may specify various output options. Specify an option by setting its value to +I. For example, +4 prints the elemental data. The print options create an ASCII output file that you can print. The write options create an unformatted output file that is accessed through a post-processor.

Line 24: **NOFOUT,(NOUT(I),I=1,NOFOUT)**

NOFOUT Number of output flags to be specified

NOUT(I) Output flag from Table 2-3

Line 25: **NOFPRT**

NOFPRT Number of print intervals

Note: If you set NOFPRT to zero, nothing will be written or printed and Line 26 must not be entered.

Line 26: **PTS,PDT, PTF**

.
.
.

PTS	Print interval start time
PDT	Print interval increment
PTF	Print interval stop time

Note: Repeat Line 26 NOFPRT times.

Line 27: **VORGET**

VORGET	External input data file name where the processed wall-vorticity data are stored. If a vorticity equation is solved, and a blank line is entered as the file name, specify the wall-vorticity flags and distances in Subsection 2.8. Using the information provided in Subsection 2.8, the software computes the geometric locations of the internal points away from the wall (used in wall-vorticity definitions).

Note: Avoid this time consuming process by using the data obtained from a previous simulation. For the initial simulation, the data must be entered at Subsection 2.8, and in the same simulation, output option O(25) is used to write the processed data into a file.

Note: The format of this file is given in Appendix A. Create the data in double precision using IMPLICIT REAL *8 (A-H, O-Z).

Table 2-3: Output Flags

O(I)	Action
1	Print title
2	Print master control parameters
3	Print position counters
4	Print elemental data
5	Print material properties
6	Print nodal data
7	Print boundary condition set value
8	Print prescribed value
9	Print constant parameters
10	Print inter-element radiation node flags
11	Print radiation view factors
12	Print Script-F factors
13	Print wall vorticity information
14	Print point source, heat moisture, and concentration generation
15	Print processed moisture data
19	Print convergence information

Table 2-3: Output Flags (continued)

O(I)	Action
20	Write control file into <FL>.CTL (for developer)
21	Write velocity vector, heat flux, moisture flux, or contaminant flux into <FL>.FLX file
22	Write mesh data into <FL>.MSH file for plotting the mesh
23	Write the converged values of the nodal unknowns into <FL>.RES file to either be used in various plots such as the x-y type plot, or contour plot, or to be used as the initial guess values in a different simulation. This file in a succeeding simulation can be used as input to Subsection 2-1, Lines 25 and 26
24	Write radiation view factor data into <FL>.VIW file. This file in a succeeding simulation can be used as input to Subsection 2-1, Line 24
25	Write processed wall-vorticity data into <FL>.VOR file. This file in a succeeding simulation can be used as input to Subsection 2-1, Line 23
31	Print x, y, and z velocity components
32	Print heat fluxes in x, y, and z directions
33	Print moisture fluxes in x, y, and z directions
34	Print contaminant fluxes in x, y, and z directions
35	Print stress components
50	Trace input file title and subtitles
250+I	Print nodal unknowns of N-th equation at each iteration
500+I	Print converged values of nodal unknowns of N-th equation

Line 28: **VIWGET**

VIWGET External input data file name where the radiation view factor data are stored. If thermal radiation is modeled, and a blank line is entered as the file name the inter-element radiation must be specified in Subsection 2.9. Using the information provided in Subsection 2.9, the software computes the view factors and performs multiple levels of shadow checking.

Note: Avoid this time consuming process by using the data obtained from a previous simulation. For the initial simulation the data must be entered at Subsection 2.9, and in the same simulation, output option O(24) can be used to write the processed data into a file.

Note: The format of this file is given in Appendix A. Create the data in double precision using IMPLICIT REAL *8 (A-H, O-Z).

Line 29: **INIGET**

INIGET External input data file name where the initial conditions are stored. This file allows you to specify the initial conditions through an input file. The format of this file is the same as <FL>.RES. This file can either be prepared by you or created by the program using the output option O(23) from a previous simulation. In the initial condition specification (Subsection 2.1, Line 7) the value of VO must be set to -32767 for the equations where the initial conditions are to be read from this file. If VO $\neq$ -32767, use the value of VO given in Line 7 as the initial condition. The data from INIGET may also be used as an initial guess for nonlinear problems.

Note: The format of this file is given in Appendix A. Create the data in double precision using IMPLICIT REAL *8 (A-H, O-Z).

Line 30: **USEGET**

USEGET — External input data file name that contains the nodal unknowns for equations that are not solved but needed in other equations. In Line 6, if you enter a negative equation number, the nodal unknowns pertaining to these equations must be in this file. You may create this file, or it can be automatically created by using output option O(23) from a previous simulation.

Note: The format of this file is the same as <FL>.RES and is given in Appendix A. Create the data in double precision using IMPLICIT REAL *8 (A-H, O-Z).

Note: In Line 6 of the USEGET file, STIM and MODE indicate the simulation time and simulation mode, respectively. If you use a steady-state data set in a transient simulation, set the value of MODE to zero in the USEGET file. If you create the USEGET file with the option of MODE 0, the program uses the same data set at each time step. If the USEGET file is created with the option of MODE 1, then at each time step a new data set is used.

Line 31: **MSHGET**

MSHGET — External input data file name that contains the mesh generation program. You may create this file by using a different mesh generation program, but if the mesh is generated using a different software, the output format must be compatible. If you specify the mesh through this file then Subsections 2.2, 2.3, and 2.7, are not used. If no file is specified, leave this line blank.

Note: The format of this file is given in Appendix A. Create the data in double precision using IMPLICIT REAL *8 (A-H, O-Z].

Line 32: **ZONGET**

ZONGET	External input data file name that contains the input for building simulations. If you want to simulate a building you must provide the file name that contains the building description. (See Section 3) If you leave the line blank, no building simulation will be performed.

2.2 NODE GENERATION

In this subsection, enter the node generation data required by the software.

CAUTION: Do not enter the data in this subsection if the input data file MSHGET (Subsection 2.1, Line 27) is used.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating node generation data. (A dummy variable used only to enhance readability of the data file).

Line 2: **NS, NI, NF, SP, XS, YS, ZS, XF, YF, ZF**

.
.
.

NS	Starting node number
NI	Increment or decrement added to get the next node. For single node generation set NI to 0.
NF	Final node number in the generation sequence
SP	Spacing factor. Use this factor for grading the mesh by gradually increasing or decreasing the distance between the nodes depending on the value input. The distance between the present node and the next node will be equal to the distance of the present node and the previous node multiplied by this value.
XS	Starting node's x-coordinate [m]
YS	Starting node's y-coordinate [m]

ZS	Starting node's z-coordinate [m]
XF	Final node's x-coordinate [m]
YF	Final node's y-coordinate [m]
ZF	Final node's z-coordinate [m]

Note: If the entry of a nodal coordinate is -32767, assume that the nodal coordinate has been previously generated and take no further action. Repeat this line as many times as required to generate the desired number of nodes.

CAUTION: Complete this subsection with a line containing 10 zeros.

2.3 ELEMENT GENERATION

In this subsection, enter the element generation data required by the software.

CAUTION: Do not enter the data in this subsection if the input data file MSHGET (Subsection 2.1, Line 27) is used.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating element generation data. (A dummy variable used only to enhance readability of the data file).

Line 2: **NS, NI, NF, MS, AR, NA, (NN(I), I- 1,NON)**

.
.
.

NS	Starting element number
NI	Increment or decrement added to get the next element. For single element generation set NI to 0.
NF	Final element number
MS	Material set number
AR	Element area for 1-D elements, thickness for 2-D and 3-D elements. It can be set to zero [m^2 of m]
NA	Increment added to each node of the previous element's node numbers to get the node numbers of the next element.

NN — Nodal connectivity. Enter the modal connectivity of the first element depending upon the element type you use in the simulations. (See Subsection 2.1, Line 2) Each element will require NON number of node numbers to describe the element. Figure 2-3 gives the local nodal connectivity sequence, and you must enter the corresponding global node numbers for the first element in the generation sequence.

Note: Repeat this line as many times as required to generate the desired number of elements.

CAUTION: Complete this subsection with a line containing 6+NON zeros.

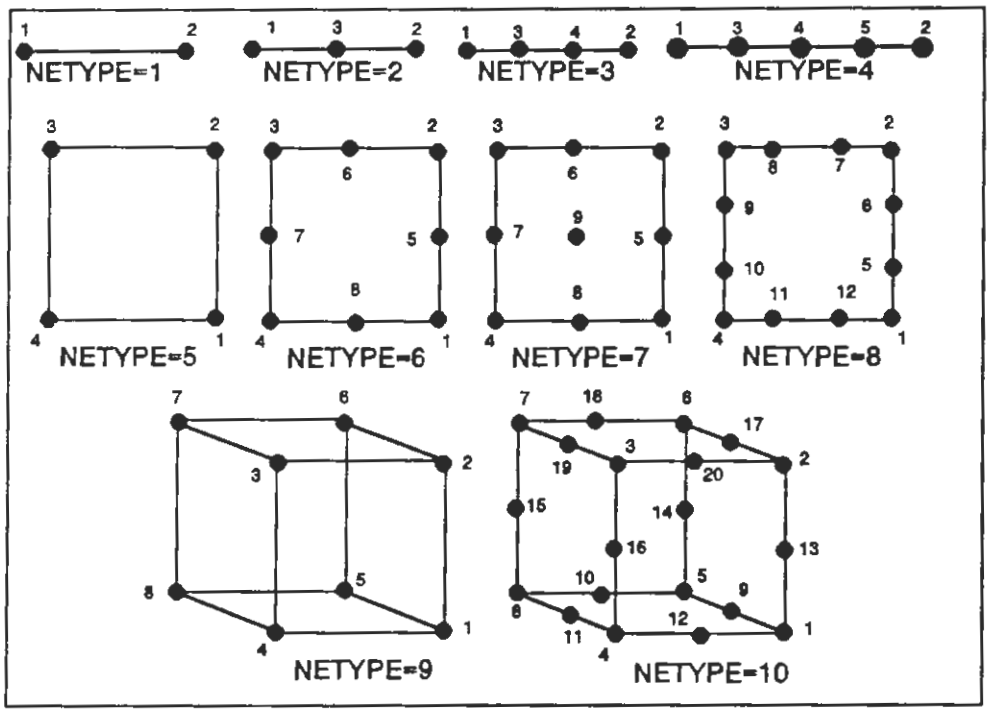

Figure 2-3: Numbering Convention for Nodal Connectivity of Different Element Types

Example of Node and Element generation:

This example consists of two parts, node generation and element generation. The example of node generation also demonstrates the use of the Spacing Factor (SP), which allows you to grade the mesh. The domain is discretized in this example using 15 elements and 24 nodes.

A simple way of discretizing is to provide equal distances between the nodes in the x-direction and equal distance between the nodes in the y-direction. Perform the node generation in this manner:

1	1	4	1.0	0.0	0.0	0.0	0.0	2.0	0.0
21	1	24	1.0	5.0	0.0	0.0	5.0	2.0	0.0
1	4	21	1.0	0.0	-32767	0.0	5.0	-32767	0.0
2	4	22	1.0	0.0	-32767	0.0	5.0	-32767	0.0
3	4	23	1.0	0.0	-32767	0.0	5.0	-32767	0.0
0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

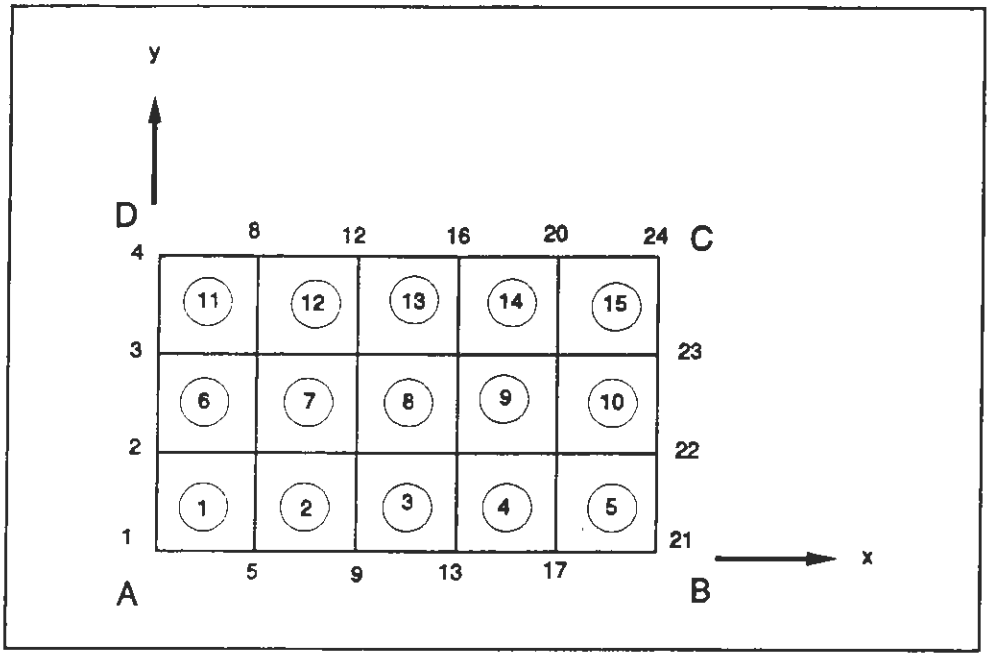

Figure 2-4: Example of Node and Element Generation

In the first line of data, the nodes are generated along the edge AD and in the second line the nodes are generated along the edge BC. After the second line, the nodes are generated along the x-axis. The y-coordinates have a value of -32767 to indicate to the software that these coordinates have already been generated and only the x-coordinate values need to be calculated.

If you want finer elements near the B corner and coarser elements away from the B corner, change the Spacing Factor provided in the fourth column of the input data for the node generation as shown:

1	4	2.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
21	1	24	2.0	5.0	0.0	0.0	5.0	2.0	0.0
1	4	21	0.5	0.0	-32767	0.0	5.0	-32767	0.0
2	4	22	0.5	0.0	-32767	0.0	5.0	-32767	0.0
3	4	23	0.5	0.0	-32767	0.0	5.0	-32767	0.0
0	0	0	0.5	0.0	0.0	0.0	0.0	0.0	0.0

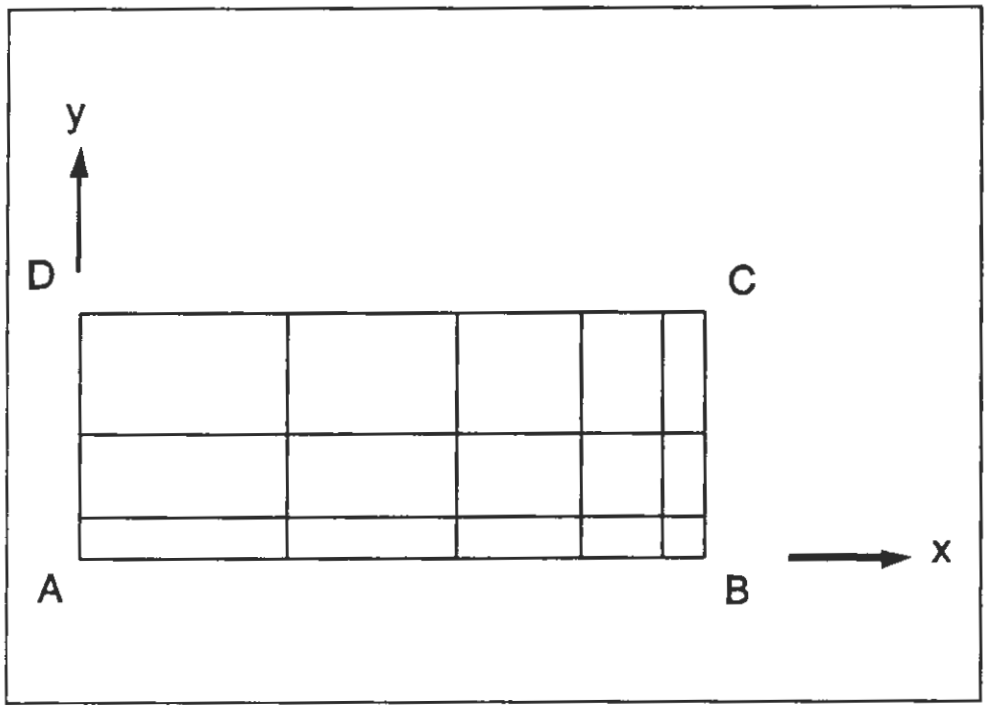

Figure 2-5: Example of Graded Mesh Generation

Element generation follows node generation in the preparation of the input deck. The element generation for Figure 2-5 is given below. Number the elements starting from the corner marked A and continue along the row or column. The connectivity for the first element is given by 5 6 2 1. Enter the order of the connectivity as shown in Figure 2-3, based on a local nodal numbering sequence. If the elements are numbered along the rows, the second element will have a connectivity of 9 10 6 5 and the third element will have a connectivity of 13 14 10 9. If you add 4 to each node number of the first element of the row, the connectivity of the second element can be obtained. Similarly, if you add 4 to the nodes of the second element, the connectivity of the third element in the row can be obtained.

The data for element generation for the first row:

1	1	5	1	1.0	4	5	6	2	1

The elements that are generated in the second row:

6	1	10	1	1.0	4	6	7	3	2

The complete data for element generation used in the input deck:

1	1	5	1	1.0	4	5	6	2	1
6	1	10	1	1.0	4	6	7	3	2
11	1	15	1	1.0	4	7	8	4	3
0	0	0	0	0	0	0	0	0	0

2.4 MATERIAL PROPERTY SPECIFICATION

In this subsection, enter material properties for NOFMAT. (Subsection 2.1, Line 2) Identify the material property of each element by the material set number used in the element generation of Subsection 2.3, Line 2. The order used in the material specification must correspond to the material set numbers used in the element generation. In other words, the first material defined in this subsection will have a material set number of 1, the second a material set of 2 and so on. Specify material properties only for the equations that are solved and set the rest of the material properties to 0.

Note: Line 3 contains thermal properties; Lines 4 and 5, moisture properties; Line 6, contaminant properties; and Line 7, fluid flow properties; Line 10, Radon transport properties. For your own equations you may use any of the **Not used** properties. For details of equations and material properties you may use, see Section 4.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating material property data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **SUBT**

SUBT	Alphanumerical input indicating the material name. (A dummy variable used only to enhance the readability of the data file).

Line 3: **(PRO(I) I=01,10)**

PRO(01)	Effective thermal conductivity, k or $(k)_e$ [W/m.K]
PRO(02)	Effective density, ρ or $(\rho)_e$ [kg/m^3]
PRO(03)	Bulk density ρ_b [kg/m^3]

PRO(04) Effective specific heat at constant pressure, C_p or $(C_p)_e$ [J/kg.K]

PRO(05) Emissivity, ϵ [dimensionless].

PRO(06) Absorptivity, α [dimensionless].

PRO(07) Transmittance, τ [dimensionless].

PRO(08) Not used
PRO(09) Not used

PRO(10) Uniform heat generation within the element, Q_T [W/m^3]

Line 4: **(PRO(I), I=11,20)**

PRO(11) Effective vapor diffusivity, D_v or $(D_v)_e$ [m^2/s]

PRO(12) Tortuosity, τo [dimensionless].

PRO(13) Porosity, Λ [$m^3_{\text{pore space}}/m^3_{\text{bulk space}}$].

PRO(14) Isothermal moisture capacity based on vapor density, A_T [m^3/kg]

PRO(15) Thermo-gradient coefficient based on vapor density, B_ρ [kg/kg.K]

PRO(16) Sorption curve parameter, a [dimensionless].

PRO(17) Sorption curve parameter, b [dimensionless].

PRO(18) Sorption curve parameter, c [dimensionless].

PRO(19) Sorption curve parameter, d [dimensionless].

PRO(20) Heat of sorption, λ [J/kg]

Line 5: **(PRO(I), I=21,30)**

PRO(21)	Moisture conductivity, k_M [kg/m.s.°M]
PRO(22)	Isothermal moisture capacity, C_M [kg/kg.°M]
PRO(23)	Ratio of vapor diffusivity to total diffusivity (liquid and vapor), γ [dimensionless].
PRO(24)	Thermo-gradient coefficient, δ [°M/K]
PRO(25)	Not used
PRO(26)	Not used
PRO(27)	Not used
PRO(28)	Not used
PRO(29)	Not used
PRO(30)	Uniform moisture generation within the element, Q_M [kg/m^3]

Line 6: **(PRO(I), I=31,40)**

PRO(31)	Molecular diffusivity of contaminant in air, D_C or $(D_C)_e$ [m^2/s]
PRO(32)	Not used
PRO(33)	Not used
PRO(34)	Not used
PRO(35)	Not used
PRO(36)	Not used
PRO(37)	Not used
PRO(38)	Not used
PRO(39)	Not used
PRO(40)	Uniform contaminant generation within the element, Q_C [kg/m^3]

Line 7: **(PRO(I), I=41,50)**

PRO(41)	Molecular viscosity, μ or μ_c [kg/m.s]
PRO(42)	Contaminant expansion coefficient, β_C [m^3/kg]
PRO(43)	Moisture expansion coefficient, β_M [m^3/kg]
PRO(44)	Thermal expansion coefficient, β_T [K^{-1}]
PRO(45)	Not used
PRO(46)	Not used
PRO(47)	Not used
PRO(48)	Not used
PRO(49)	Not used
PRO(50)	Not used

Line 8: **(PRO(I), I=51,60)**

PRO(51)	Modulus of elasticity, E_{xx}
PRO(52)	Modulus of elasticity, E_{yy}
PRO(53)	Modulus of elasticity, E_{zz}
PRO(54)	Poisson's ratio, μ_{xx}
PRO(55)	Poisson's ratio, μ_{yy}
PRO(56)	Poisson's ratio, μ_{zz}
PRO(57)	Not used
PRO(58)	Not used
PRO(59)	Not used
PRO(60)	Not used

Line 9: **(PRO(I), I=61,70)**

PRO(61)	Coefficient of thermal expansion, α_T or $\alpha_T \Delta T$
PRO(62)	Coefficient of moisture expansion, α_M or $\alpha_M \Delta M$
PRO(63)	Not used
PRO(64)	Not used
PRO(65)	Not used
PRO(66)	Not used
PRO(67)	Not used
PRO(68)	Body force in x-direction, b_x
PRO(69)	Body force in y-direction, b_y
PRO(70)	Body force in z-direction, b_z

Line 10: **(PRO(I), I=71,80)**

PRO(71)	^{222}Rn diffusion coefficient in air, D_{ao} [1.1×10^{-5} m^2/s]
PRO(72)	Dry-surface adsorption coefficient for ^{222}Rn, $k_a°$ [m^3/kg]
PRO(73)	Adsorption-moisture correlation constant, b [dimensionless]
PRO(74)	Bulk soil air permeability, K [m^2]
PRO(75)	Soil ^{226}Ra concentration (dry basis), R [Bq/m^3]
PRO(76)	^{226}Ra equilibrium distribution coefficient in solid-to-pore liquid, k_d [m_3/kg] (If not used, then set to zero)
PRO(77)	Total Radon emanation coefficient, $E_{air+water}$ [dimensionless]

PRO(78) Reference pressure, P_o [Pa]

PRO(79) Moisture saturation fraction, m [V_w/V_{bulk}]

PRO(80) Arithmetic average particle diameter, d_a [m]

Line 11: **(PRO(I), I=81,90)**

PRO(81) Radon distribution coefficient (water/air) from Henry's law, k [.26 at 20°C]

PRO(82) Not used
PRO(83) Not used
PRO(84) Not used
PRO(85) Not used
PRO(86) Not used
PRO(87) Not used
PRO(88) Not used
PRO(89) Not used
PRO(90) Not used

Line 12: **(PRO(I), I=91,100)**

PRO(91) Not used
PRO(92) Not used
PRO(93) Not used
PRO(94) Not used
PRO(95) Not used
PRO(96) Not used
PRO(97) Not used
PRO(98) Not used
PRO(99) Not used
PRO(100) Not used

Note: Repeat Lines 2 through 12 NOFMAT times.

Table 2-4 gives the material properties required by each equation. Depending upon the combination of equations solved, all material properties may not be required.

Table 2-4: Material Properties Required for Each Equation

NEQ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1										X	X	X									
2	X	X	X		X			X	X	X	X	X			X			X	X	X	X
3										X[4]	X[4]		X	X							
4										X	X	X									
5										X	X										
6																					
7																					
8																					
9																					
10													X	X							
11													X	X							
12													X	X							
13													X	X							
14										X[4]	X[4]		X	X							
15										X[4]	X[4]		X	X							
16													X[6]	X[6]							
17													X[6]	X[6]							
18													X[6]	X[6]							
19													X[6]	X[6]							
20										X[4]	X[4]	X									
21												X			X						
22															X						
23												X									
24												X			X						
25																					
26																					
27																					
28																					
29																					
30																					
31													X	X							
32																					
33																					
34																					
35																					

Table 2-4: Material Properties Required for Each Equation (continued)

NEQ	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					
13																					
14																					
15																					
16																					
17																					
18																					
19																					
20																					
21																					
22																					
23																					
24																					
25				X				X													
26	X	X	X	X	X	X	X		X	X	X										
27																					
28																					
29																					
30																					
31																					
32																					
33																					
34																					
35																					

Table 2-4: Material Properties Required for Each Equation (continued)

NEQ	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
36																					
37																					
38																					
39																					
40																					
41	X	X	X		X					X[5]	X[5]							X	X	X	X
42	X[1]	X[1]	X[1]		X													X[1]	X[1]	X[1]	X
43	X[2]	X[2]	X[2]		X													X[2]	X[2]	X[2]	X
44	X[3]	X[3]	X[3]		X													X[3]	X[3]	X[3]	X
45																					X
46																					
47																					
48																					
49																					
50																					

[1] If concentration equation (NEQ = 16) is solved, and concentration buoyancy is simulated.
[2] If moisture equation (NEQ = 13) is solved, and moisture buoyancy is simulated.
[3] If energy equation (NEQ = 10) is solved, and thermal buoyancy is simulated.
[4] If combined heat and moisture equations are solved together.
[5] If viscous dissipation is simulated.
[6] If A_T and B_ρ values are not provided then these values needs to be supplied. The same is also valid for NEQ = 10.
[7] If D_v is not provided then this value is required.

For buoyancy simulations the components of the acceleration due to gravity vector must be supplied [CON(1) - CON(3)]. If the fluid flow equations in primitive variables along with buoyancy terms are solved then the reference conditions must be supplied [CON(4) - CON(6)].

If the fluid flow equations are solved in the primitive variables the penalty parameter CON(26) must be supplied.

In the turbulence modelling, the empirical constants used in the κ-ϵ model must be supplied [CON(11) - CON(19)].

If thermal radiation is modelled the value of Stefan-Boltzmann constant must be supplied.
If combined heat and moisture transfer is modelled the value of barometric pressure CON(22) and ideal gas constant CON(23) must be supplied.

Note: The equation descriptions are given in Table 2-2 and the formulations of the equations are given in CHAPTER 5.

2.5 BOUNDARY CONDITION SET VALUE SPECIFICATION

In this subsection, enter the boundary condition values for NOFBCO (Subsection 2.1, Line 2). For each equation simulated, each node will have a unique boundary condition set number (defined in Subsection 2.7 and termed as a boundary condition flag). The order you use in the boundary condition set value specification corresponds to the boundary condition flags assigned to each node. The first boundary condition set value defined in this subsection has a boundary condition flag of 1, the second a boundary condition flag of 2 and so on. You are required to specify boundary condition values only for the equations that are simulated. Set the rest of the boundary condition values to 0.

Note: Line 3 contains thermal boundary condition values; Lines 4 and 5, moisture boundary condition values; and Line 6, contaminant boundary condition values.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating boundary condition set value data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **SUBT**

SUBT	Alphanumerical input indicating boundary condition set value data. (A dummy variable used only to enhance the readability of the data file).

Line 3: **(BCO(I), I=01,10)**

BCO(01)	Convective heat transfer coefficient, h_T [W/m^2.K]
BCO(02)	Convective fluid side temperature, T_α [K]
BCO(03)	Imposed heat flux, $q"_T$ [W/m^2]

BCO(04) Emitting sink or source temperature, T_s [K]

BCO(05) View factor from the boundary to sink or source, F_s [dimensionless].

BCO(06) Not used
BCO(07) Not used
BCO(08) Not used
BCO(09) Not used
BCO(10) Not used

BCO(1) through BCO(10) are boundary condition specifications for the energy equation (NEQ = 10,11 or 12).

Line 4: <u>(BCO(I), I=11,20)</u>

BCO(11) Convective moisture transfer coefficient, h_M [m/s]

BCO(12) Convective fluid side water vapor density, $\rho_{v,\alpha}$ [kg/m^3]

BCO(13) Imposed moisture flux, q''_M [kg/m^2.s]

BCO(14) Not used
BCO(15) Not used
BCO(16) Not used
BCO(17) Not used
BCO(18) Not used
BCO(19) Not used
BCO(20) Not used

BCO(11) through BCO(13) are boundary condition specifications for the vapor density equation (NEQ = 13 or 14).

Line 5: **(BCO(I), I=21,30)**

BCO(21)	Convective mass transfer potential coefficient, $h_{M,M}$ [kg/m^2.s.°M]
BCO(22)	Convective fluid side mass transfer potential, M_α [°M]
BCO(23)	Not used
BCO(24)	Not used
BCO(25)	Not used
BCO(26)	Not used
BCO(27)	Not used
BCO(28)	Surface traction in x-direction, s_x
BCO(29)	Surface traction in y-direction, s_y
BCO(30)	Surface traction in z-direction, s_z

BCO(21) through BCO(22) are boundary condition specifications for the Luikov's mass transfer potential equation (NEQ = 15).

Line 6: **(BCO(I), I=31,40)**

BCO(31)	Convective contaminant transfer coefficient, h_C [m/s]
BCO(32)	Convective fluid side contaminant concentration, C_α [kg/m^3]
BCO(33)	Imposed contaminant flux, $q"_C$ [kg/m^2.s]
BCO(34)	Not used
BCO(35)	Not used
BCO(36)	Not used
BCO(37)	Not used
BCO(38)	Not used
BCO(39)	Not used
BCO(40)	Not used

Lines BCO(31) through BCO(33) are boundary condition specifications for the concentration equation (NEQ = 16 or 17).

Note: Repeat Lines 2 through 6 NOFBCO times.

2.6 PRESCRIBED VALUE SPECIFICATION

In this subsection, enter the prescribed value specification data required by the software.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating boundary condition flag generation data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **PV**

.
.
.

PV	Prescribed value

Starting with Line 2, the prescribed values sets are specified. Repeat Line 2, NOFPRS (defined in Subsection 2.1, Line 2), as many times as needed to specify all the prescribed values.

Note: The value specified in Line 2 is the first prescribed value and the one defined in the n-th line of this subsection is the n-1th prescribed value. The specification of this boundary condition is similar to the boundary condition set value specification discussed in Subsection 2.5. Applications of boundary condition set values and prescribed values are discussed in Subsection 2.7.

2.7 BOUNDARY CONDITION FLAG GENERATION

In this subsection, enter the boundary condition flag generation data required by the software.

CAUTION: Do not enter the data in this subsection if the input data file MSHGET (Line 27) is given. For higher order elements use only the corner or end nodes to determine the application of boundary condition flags.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating boundary condition flag generation data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **NS, NI, NF, (NBC(NUMEQN(I)), I=1,NOFEQN)**

.
.
.

NS	Starting node number
NI	Increment or decrement added to get the next node. For single node specification set NI to 0.
NF	Final node number
NBC	Boundary condition flag for the NUMEQN(I)-th equation. The numerical value and the sign of the boundary condition flag determine the type of the boundary condition to be associated with the node(s) generated in this sequence.

If NBC < 0 then 2nd or 3rd kinds of boundary conditions will be used. In other words, for
| NBC(NUMEQN(I)) | the set of boundary condition specified in Subsection 2.5 will be applied.

If NBC is 0, then the boundary is assumed to be insulated or impermeable. In a natural boundary condition the first derivative of the field variable is set to 0).

If NBC > 0 then the NBC-th prescribed boundary condition defined in Subsection 2.6 is applied.

Note: In the case of a vorticity equation, -1 and -2 boundary condition flags denote wall-vorticities. If the flag is -1, the true surface is normal. If the flag is -2, a vector connecting the node to the centroid of the element is used to determine the internal stream function points used in wall vorticity formulations. Repeat Line 2 as many times as needed to define the boundary condition flags.

CAUTION: Complete this subsection with a line containing (3+NOFEQN) zeros.

2.8 WALL VORTICITY DISTANCE SPECIFICATION

In this subsection, enter the wall-vorticity distance specification data required by the software.

CAUTION: Do not use this subsection if you do not solve the vorticity equation, or if you input the processed wall-vorticity conditions through the VORGET file (Subsection 2.1, Line 23). In this subsection, input the distances, Δn, to be used in the wall-vorticity equations, for all nodes where the vorticities are calculated using the equations in Subsection 2.1, Line 5. In Subsection 2.7, the wall-vorticity flags are generated for the wall nodes. For each node flagged with a -1 or -2 wall-vorticity boundary condition flag, enter an appropriate distance.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating wall vorticity distance specification data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **NS, NI, NF, DIST**

.
.
.

NS	Starting node number
NI	Increment or decrement added to get the next node. For single node specification set NI to 0.
NF	Final node number
DIST	Distance used in the wall vorticity calculations [m]

Note: Repeat Line 2 as many times as needed to define the wall vorticity distances.

CAUTION: Complete this subsection with a line containing 4 zeros.

2.9 INTER-ELEMENT RADIATION SURFACE GENERATION

In this subsection enter the inter-element radiation surface generation data required by the software.

CAUTION: Do not use this subsection if you do not solve Equations 11, 12 or 13, or if you enter the view factors through the VIWGET file (Subsection 2.2, Line 24). In this subsection, flag all the nodes that are actively participating in inter-element radiation. For higher order elements use only the corner or end nodes to determine the application of inter-element radiation. If only the corner or end nodes are flagged, it is understood that the element is either an emitter or a receiver.

Line 1: **SUBT**

SUBT — Alphanumerical input indicating inter-element radiation surface generation data. (A dummy variable used only to enhance readability of the data file).

Line 2: **NS, NI, NF, NBC**

.
.
.

NS — Starting node number

NI — Increment or decrement added to get the next node. For single node specification set NI to 0.

NF — Final node number

NBC — Inter-element radiation flag

NBC Enter +1 to enable radiation for fluid elements ($\mu \neq 0$, Subsection 2.4, Line 7)

NBC Enter +0 if radiation is not considered.

NBC Enter -1 to enable radiation for solid elements (i.e. $\mu = 0$, Subsection 2.4, Line 7).

NBC Enter -2 to denote that the particular node is a junction for solid and fluid legs. The flag of the other node of the element leg determines if radiation is to be activated.

Note: Inter-element radiation flags may not be activated on the opposite legs of the same element. For a given element, all of the legs cannot emit. Repeat Line 2 as many times as needed to define the inter element radiation flags.

CAUTION: Complete this subsection with a line containing 4 zeros.

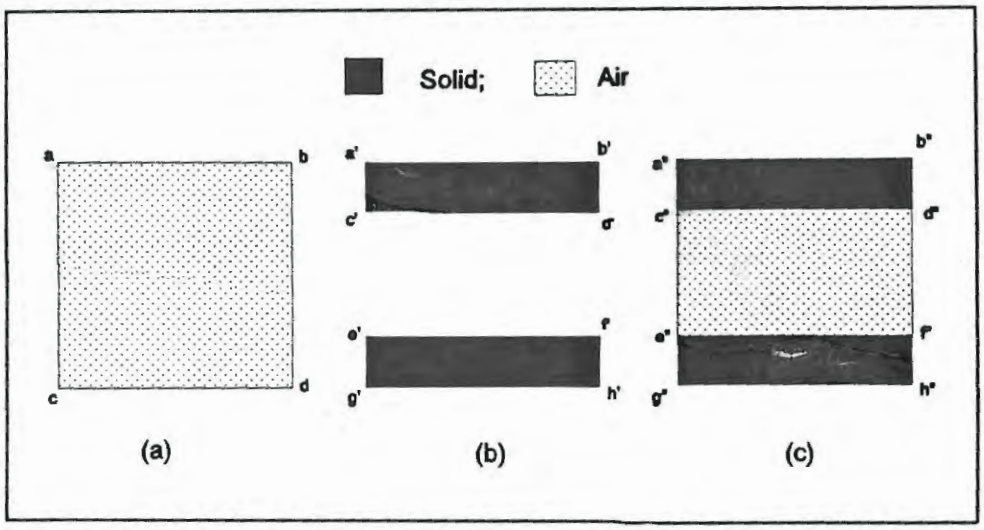

Figure 2-6: Convention for Radiation Boundary Condition Generation

Example of radiation exchange:

In case (a), radiation exchange is taking place along ab and cd and only fluid is simulated. Fluid is defined by its viscosity being non-zero. Flag the nodes along ab and cd using +1.

In case (b), radiation exchange is taking place along c'd' and e'f'. In this example one solid is radiating to another solid. Flag the nodes along c'd' and e'f' using -1.

In case (c), radiation exchange is taking place along c"d" and e"f". In this example one solid is radiating to another solid, but the solids are connected by fluid elements. Flag the nodes along c"d" and e"f" using -2.

2.10 POINT SOURCE SPECIFICATION

In this subsection, enter the point source specification data required by the software.

Line 1: **SUBT**

SUBT	Alphanumeric input indicating point source specification data. (A dummy variable used only to enhance the readability of the data file).

Line 2: **NOFSOR**

NOFSOR	Number of point sources

Line 3: **NEQ, XCOR, YCOR, ZCOR, VALUE**

.
.
.

NEQ	Equation number for which the point source is to be considered
XCOR	X-coordinate of the location of the point source
YCOR	Y-coordinate of the location of the point source
ZCOR	Z-coordinate of the location of the point source
VALUE	The magnitude of the point source. Typical units for different library equations. (See Table 2-5)

Note: If the values of XCOR, YCOR, ZCOR, and VALUE are functions of time and/or any other field variable, use a negative number less than -1000 to define their value through Subroutine VRPROP.

Table 2-5: Point Source Units and Definitions.

NEQ	Units	Definition
10	W	Point heat source
11	W	Point heat source
12	W	Point heat source
13	kg/s	Point moisture source
14	kg/s	Point moisture source
15	kg/s	Point moisture source
16	kg/s	Point contaminant source
17	kg/s	Point contaminant source
22	$kg.m/s^2$	Point load in x-direction source
23	$kg.m/s^2$	Point load in y-direction source
24	$kg.m/s^2$	Point load in z-direction source

SECTION 3

BUILDINGS PROGRAM INPUT FILE

INTRODUCTION

This section describes the preparation of the input file required by the buildings program line by line. Use this identifiable format to input each line:

Line number: variable 1, variable 2,..., variable n.

Numerical input variables are read by the program using free format, the input data must be separated by commas or spaces. Long lists of variables may continue on succeeding lines. In certain lines, vertical ellipses, three dots aligned on top of each other, indicate the input line may be repeated as many times as needed. Use any engineering units, but consistency throughout the input deck is required by the program. However, the unit of time must be given in seconds. All units have to be Systeme Internationale unit except the input of simulation time, which is hour basis.

3.1 MASTER CONTROL

This subsection provides the master control data used by the buildings program. Five lines of input must be provided.

Line 1: **TITLE**

TITLE — Alphanumerical problem title is maximum 80 characters long. The title line is printed in appropriate places, such as examples, hardback copies, and output files to distinguish between different simulations. The title is an optional input. You may decide to leave a blank line.

Line 2: **NOFZON, NOFSCH, NOFSUR, MODZON, NORFLG**

NOFZON — Total number of zones used in the simulation

NOFSCH — Total number of schedules defined in Subsection 3.2

NOFSUR — Total number of heat and/or moisture transfer surfaces used in the simulation and defined in Subsection 3.4

MODZON — Combined heat and moisture simulation mode

- MODZON — Enter 0 for solving only energy equation.
- MODZON — Enter 1 for solving energy equation with lumped moisture equations for the walls.
- MODZON — Enter 2 for solving distributed energy and moisture equations.

NORFLG — Flag for Mean Radiant Temperature (MRT) calculation.

- NORFLG — Enter 0 for non MRT calculation.

NORFLG Enter 1 for MRT calculation.

Line 3: NBLD, NOFEQB, (NEQ(I),I=1,NOFEQB)

NBLD Solution procedure

- NBLD Enter 0 when each equation at one zone is solved at a time.
- NBLD Enter 1 when each equation at all zones is solved simultaneously.
- NBLD Enter NOFEQB when all equations at all zones are solved simultaneously.

NOFEQB Number of equations solved

NEQ Equation number defined Table 3-1

Table 3-1: Equation Library of Zone Balance

No	Symbole	Equation Name
1	T	Energy balance
2	W	Moisture balance
3	C_1	Species 1 balance
4	C_2	Species 2 balance
5	C_3	Species 3 balance
6	.	For future use
7	.	For future use

Line 4: **SDAY, SHOUR, EDAY, EHOUR, TSTP**

SDAY	Provide simulation start date in Julian day
SHOUR	Provide simulation start hour in hours
EDAY	Provide simulation stop date in Julian day
EHOUR	Provide simulation stop hour in hours
TSTP	Provide simulation time step in hours

Note: The information in Line 3 overwrites the information provided in Section 2. (See Subsection 2.1, Line 3)

Line 5: **(CONST(I), I=1,10)**

CONST(01)	Density of zone air [1.18kg/m^3]
CONST(02)	Specific heat of zone air [1007J/kg.K]
CONST(03)	Latent heat of vaporization [2.4x10^6J/kg]
CONST(04)	Not used
CONST(05)	Not used
CONST(06)	Not used
CONST(07)	Not used
CONST(08)	Not used
CONST(09)	Not used
CONST(10)	Not used

Line 6: (CONST(I), I=11,20)

CONST(11) Primary mechanical unit total capacity [W]

CONST(12) Auxiliary mechanical unit sensible capacity [W]

CONST(13) Auxiliary mechanical unit latent capacity [kg/s]

CONST(14) Not used

CONST(15) Sensible heat fraction for primary mechanical unit [dimensionless].

CONST(16) Coefficient of performance of the primary mechanical unit [dimensionless].

CONST(17) Coefficient of performance of the auxiliary mechanical unit [dimensionless].

CONST(18) Not used
CONST(19) Not used
CONST(20) Not used

Line 7: (CONST(I), I=21,30)

CONST(21) Not used
CONST(22) Not used
CONST(23) Not used
CONST(24) Not used
CONST(25) Not used
CONST(26) Not used
CONST(27) Not used
CONST(28) Not used
CONST(29) Not used
CONST(30) Not used

Line 8: **(CONST(I), I=31,40)**

CONST(31)	Not used
CONST(32)	Not used
CONST(33)	Not used
CONST(34)	Not used
CONST(35)	Not used
CONST(36)	Not used
CONST(37)	Not used
CONST(38)	Not used
CONST(39)	Not used
CONST(40)	Not used

Line 9: **(CONST(I), I=41,50)**

CONST(41)	Not used
CONST(42)	Not used
CONST(43)	Not used
CONST(44)	Not used
CONST(45)	Not used
CONST(46)	Not used
CONST(47)	Not used
CONST(48)	Not used
CONST(49)	Not used
CONST(50)	Not used

Note: The constant array, CONST(I), defined in Lines 4-8 is transferred to routines you define. They may be used to specify the constants in routines you define. (See Subsection 3.8 for examples). The constant array, CONST(I), is stored in XL array location NCR(11)+MAXCON+I in the program, where MAXCON is maximum number of constant used in FEM input.

Line 10: **(O(I), I=1,10)**

O(01) Write both temperature and sensible load and components into an output file. The fields of the output file:

FIELD	DESCRIPTION
1	Zone number
2	Time of year [h]
3	Zone temperature [C]
4	Sensible load due to infiltration [W]
5	Sensible load due to solar through windows [W]
6	Sensible storage in the zone [W]
7	Sensible load due to ventilation [W]
8	Sensible load due to conduction [W]
9	Sensible load due to internal generation [W]
10	Total sensible load [W]

O(02) Write zone humidity ratio and latent load with its components into an output file. The fields of the output file:

FIELD	DESCRIPTION
1	Zone number
2	Time of year [h]
3	Zone humidity ratio [kg/kg]
4	Latent load due to infiltration [W]
5	Latent storage in the zone [W]
6	Latent load due to ventilation [W]
7	Latent load due to diffusion [W]
8	Latent load due to internal generation [W]
9	Total latent load [W]

O(03) Write mechanical system output file. The fields of the output file:

FIELD	DESCRIPTION
1	Zone number
2	Time of year [h]
3	Total sensible load [W]
4	Total latent load [W]
5	Sensible removal by primary mechanical unit [W]
6	Latent removal by primary mechanical unit [W]
7	Primary mechanical unit run time [fraction]
8	Primary mechanical unit power consumption [Wh]
9	Sensible removal by auxiliary mechanical unit [W]
10	Latent removal by auxiliary mechanical unit [W]
11	Auxiliary mechanical unit run time [fraction]
12	Auxiliary mechanical unit power consumption [Wh]

O(04)	Write inside and outside surface temperatures into an output file.
O(05)	Write inside and outside surface vapor densities into an output file.
O(06)	Write heat fluxes of inside and outside surfaces when Conduction Transfer Function (CTF) method is used
O(07)	Not used
O(08)	Not used
O(09)	Not used
O(10)	Not used

Note: The output option flags, O(I), are activated by setting the value of O(I) to a positive integer number that is greater than 30 and less than 100. The positive integer number indicates the logical output unit number, and the output file name. For example, if O(1) is set to 35 then the zone temperatures and sensible loads are written into FOR035.DAT.

3.2 SCHEDULE SPECIFICATION

This subsection requires specific daily schedules for 24 hours. Each schedule consists of 24 values and these values can be constant or vary throughout the day. Use hourly schedule values as multipliers in appropriate places. (See Subsection 3.6) The capacity of certain magnitudes are multiplied by these hourly schedule values. (See Subsection 3.6) For example, variable infiltration, ventilation, and internal generation loads can be simulated. This subsection contains NOFSCH*3+1 lines of input. (See Subsection 3.1, Line 2)

Line 1: **SUBT**

SUBT	Alphanumerical input indicating the following information is schedule data.

Line 2: **SUBT**

SUBT	Alphanumerical input indicating the schedule number.

Line 3: **(S(I), I=01,12)**

S(I)	Hourly schedule value

Line 4: **(S(I), I=13,24)**

S(I)	Hourly schedule value

Note: Lines 2-4 must be repeated NOFSCH times. The order used in the schedule specification corresponds to the schedule number used in Subsection 3.6. The intermediate schedule values are obtained by linear interpolation for simulations using time steps less than one hour.

3.3 ENVIRONMENTAL DATA SPECIFICATION

In this subsection, you provide the geographical location of the building and the environmental data file type. This subsection requires 3 lines of input.

Line 1: **SUBT**

SUBT — Alphanumerical input indicating the information is environmental specification data.

Line 2: **STDMRD, ZLATIT, ZLONGT, GRDREF,SOLFLG,JSLCOR**

STDMRD — Standard meridian [degree]

ZLATIT — Latitude [degree]

ZLONGT — Longitude [degree]

GRDREF — Ground reflectance [dimensionless]

SOLFLG — Equation of time correction flag

- SOLFLG — Enter 0 if time is specified in Subsection 3.1, Line 3.
- SOLFLG — Enter 1 if time specified in Subsection 3.1, Line 3 is modified by the equation of time.

JSLCOR — Solar diffuse to total correlation flag

- JLSCOR — Enter 1 for Liu and Jordan's correlation.
- JSLCOR — Enter 2 for Boes et al. correlation.
- JSLCOR — Enter 3 for Erb's correlation.
- JSLCOR — Enter 4 for Orgil and Holland's correlation.

Line 3: **ENVGET**

ENVGET	Use the environmental file name in the building simulation. This is a sequential data file and the format of this file is given in Table 3-1. If the you want to use a weather tape, for example, **TCY** or **TMY**, then the weather data tape must be pre-processed to match the format given in Table 3-1

Provide one period of environmental data file if you use periodic weather data file in the building simulation. The program automatically reads the data for the rest of the periods repeatedly. For example, in order to eliminate the error caused by initial conditions, run the program for several days with the same weather data file to make sure that conditions independent of time are achieved. The minimum input for the weather data file should contain ambient dry bulb temperature and humidity ratio. Horizontal solar radiation is strongly recommended.

TABLE 3-1: Environmental Data File Format

Field	Content	Units	NCR(2090)+
1	Hour of year (solar time)	h	0
2	Ambient dry-bulb temperature	K	1
3	Not used (set to 0)	-	2
4	Not used (set to 0)	-	3
5	Not used (set to 0)	-	4
6	Ambient humidity ratio	kg/kg	5
7	Sky temperature	K	6
8	Ground temperature	K	7
9	Horizontal solar radiation	W/m^2	8
10	Not used (set to 0)	-	9
11	Rain flag (0 for rain, 1 for no rain)	-	10
12	Wind speed	m/s	11
13	Wind direction	degree	12
14	Not used (set to 0)	-	13
15	Not used (set to 0)	-	14
16	Not used (set to 0)	-	15
17	Not used (set to 0)	-	16
18	Not used (set to 0)	-	17
19	Not used (set to 0)	-	18
20	Not used (set to 0)	-	19
21	Not used (set to 0)	-	20

Note: Provide each line with 21 data fields separated by commas or spaces. The data given in the environmental data file must be consistent with the simulation time step.

The environmental data is stored in location NCR(2090) of XL array in the building program.

3.4 BOUNDARY CONDITION MODIFICATION

Use this subsection to generate the heat and/or moisture transfer surfaces for the building. The surfaces may be coupled to the zone or ambient by specifying the input parameters. This subsection contains NOFSUR+1 input lines.

Line 1: **SUBT**

SUBT — Alphanumerical input indicating the information is boundary condition modification data.

Line 2: **NODE, NBCFLG, AZIMUT, TILT, AREA, EMPD**

.
.
.

NODE — Node number of the surface, as generated in Subsection 2.2.

NBCFLG — Boundary condition flag

The boundary condition flags used in the finite element mesh are created in Subsection 2.7. However, the NBCFLG here is used as a modifier to indicate the coupling of the walls to either ambient or zone as:

NBCFLG	Enter a number less than 0 if the surface is exposed to ambient conditions.
NBCFLG	Enter 0 if no action is taken.
NBCFLG	Enter a number greater than 0 if the surface is exposed to a zone. The positive value of NBCFLG will indicate the zone number that the surface is exposed to.

AZIMUT — Azimuth angle of the heat and/or moisture transfer surface [degree]. South 0, north 180, west +90 and east -90 degrees

TILT — Tilt angle of the heat and/or moisture transfer surface [degree]. Vertical surface 90^0, horizontal surface facing up (sky) 0^0 and horizontal surface facing down (ground) 1800.

AREA — Area of the heat and/or moisture transfer surface [m2]

Note: The area of the heat and/or moisture transfer surface can be either specified while generating the mesh (See Subsection 2.3) or can be specified here. If the area is specified here (AREA > 0) then the area specified in Section 2 will be overwritten by this value.

EMPD — Effective moisture penetration depth value [m]

Note: If MODZON (See Subsection 3.1, Line 2) is set to 0 or 2 this value is not used, and it can be set to 0. If MODZON is set to 1 and no surface moisture calculation is desired the value of EMPD can be set to 0 (otherwise the value supplied is used in the calculations). Line 2 must be repeated NOFSUR times.

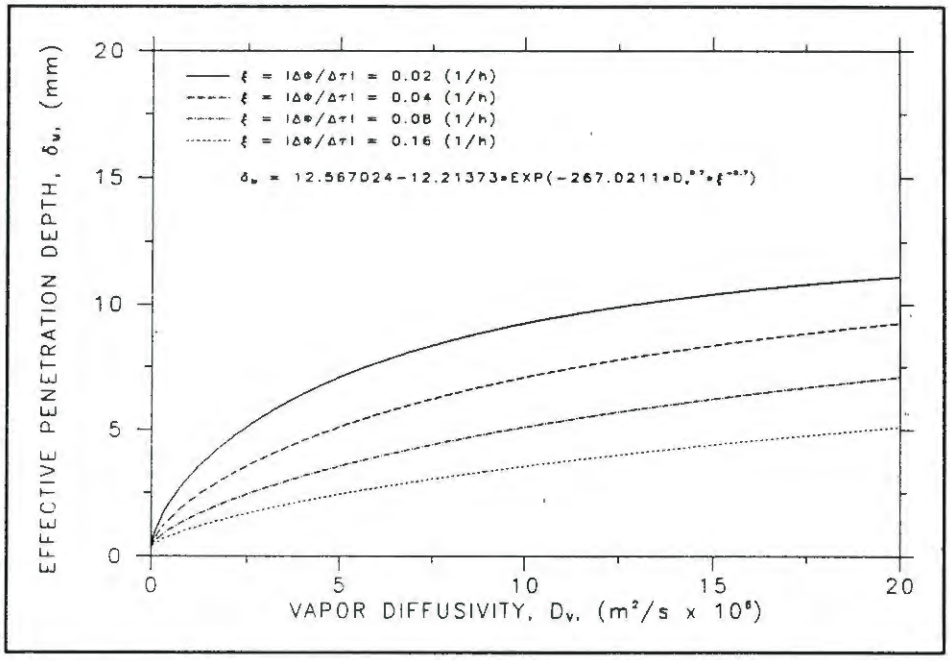

Figure 3-1: Limits of Effective Penetration Depth Values for Various Vapor Diffusivities Evaluated at Different Ambient Excitations

Figure 3-1 gives the EMPD values used for various vapor diffusivities evaluated at different ambient excitations. The vapor diffusivity is related to the permeability of the material with this equation

$$D_v = \pi R_v T$$

where,

π -- Permeability [kg/m.s.Pa]
D_v -- Vapor diffusivity [m^2/s]
R_v -- Ideal gas constant [461.52 J/kg.K]
T -- Temperature [K]

3.5 SYSTEM PARAMETERS

Line 1: **SUBT**

SUBT	Alphanumerical input indicating the information is system parameter related data.

Line 2: **MECHNO**

MECHNO	Currently not used, set to zero

3.6 ZONE DATA

This subsection contains NOFZON*15+1 INPUT LINES.

Line 1: **SUBT**

SUBT	Alphanumerical input indicating the information is zone related data.

Line 2: **SUBT**

SUBT	Alphanumerical input indicating the zone number.

Line 3: **VOLUME, TRMOLD, WRMOLD**

VOLUME	Zone volume [m^3]
TRIMOLD	Initial zone temperature [K]
WRMOLD	Initial zone humidity ratio [kg/kg]

Line 4: CAPEQP, NSCEQP, CTREQP, RFREQP, SFREQP

CAPEQP	Internal load generation due to all equipments [W]
NSCEQP	Equipment schedule number from Subsection 3.2. The hourly CAPEQP are obtained by multiplying CAPEQP by the hourly fractions used in the NSCEQP-th schedule.
CTREQP	Equipment control number. (See Subsection 3.8)
RFREQP	Radiative fraction of the equipment CAPEQP*SFREQP*RFREQP and CAPEQP*SFREQP*(1-RFREQP) are assumed to be the radiative and convective parts of the sensible load, respectively. The convective part is treated as internal heat generation and the radiative part is distributed equally among the inside wall surfaces.
SFREQP	Sensible fraction of the equipment Sensible to latent fraction of equipments CAPEQP*SFREQP and CAPEQP*(1-SFREQP) are assumed to be the sensible and latent parts of the load, respectively.

Line 5: CAPFAN, NSCFAN, CTRFAN

CAPFAN	Number of fans (currently not used, set to zero)
NSCFAN	Fan schedule number (currently not used, set to zero)
CTRFAN	Fan control number (See Subsection 3.8)

Line 6: **CAPINF, NSCINF, CTRINF**

CAPINF	Infiltration rate [ach]
NSCINF	Infiltration schedule number from Subsection 3.2. The hourly CAPINF are obtained by multiplying CAPINF by the hourly fractions used in the NSCINF-th schedule.
CTRINF	Infiltration control number (See Subsection 3.8)

Line 7: **CAPLGT, NSCLGT, CTRLGT, RFRLGT**

CAPLGT	Internal load generation due to lighting [W]
NSCLGT	Lighting schedule number from Subsection 3.2. The hourly CAPLGT is obtained by multiplying CAPLGT by the hourly fractions used in the NSCLGT-th schedule.
CTRLGT	Lighting control number (See Subsection 3.8)
RFRLGT	Radiative fraction of the lighting

Line 8: **CAPPEO, NSCPEO, CTRPEO, SFRPEO**

CAPPEO Internal load generation due to people [W]

NSCPEO People schedule number from Subsection 3.2. The hourly CAPPEO is obtained by multiplying CAPPEO by the hourly fractions used in the NSC[illegible]-th schedule.

CTRPEO People control number (See Subsection 3.8)

SFRPEO Sensible to latent fraction of people CAPEO*(1-SFRPEO) is assumed to be the sensible and latent parts of the load, respectively.

Line 9: **CAPVEN, NSCVEN, CTRVEN**

CAPVEN Ventilation rate [ach]

NSCVEN Ventilation schedule number from Subsection 3.2. The hourly CAPVEN is obtained by multiplying CAPVEN by the hourly fractions used in the NSCVEN-th schedule.

CTRVEN Ventilation control number (See Subsection 3.8)

Line 10: **SETTMX, NSCTMX, CTRTMX**

SETTMX Thermostat upper set point [K]

NSCTMX Thermostat upper set point schedule number from Subsection 3.2. The hourly SETTMX is obtained by multiplying SETTMX by the hourly fractions used in the NSCTMX-th schedule.

CTRTMX Thermostat upper set point control number (See Subsection 3.8)

Line 11: **SETTMN, NSCTMN, CTRTMN**

SETTMN	Thermostat lower set point [K]
NSCTMN	Thermostat lower set point schedule number from Subsection 3.2. The hourly SETTMN is obtained by multiplying SETTMN by the hourly fractions used in the NSCTMN-th schedule.
CTRTMN	Thermostat lower set point control number (See Subsection 3.8)

Line 12: **SETWMX, NSCWMN, CTRWMX**

SETWMX	Humidistat upper set point [kg/kg]
NSCWMX	Humidistat upper set point schedule number from Subsection 3.2. The hourly SETWMX is obtained by multiplying SETWMX by the hourly fractions used in the NSCWMX-th schedule.
CTRWMX	Humidistat upper set point control number (See Subsection 3.8)

Line 13: **SETWMN, NSCWMN, CTRWMN**

SETWMN	Humidistat lower set point [kg/kg]
NSCWMN	Humidistat lower set point schedule number from Subsection 3.2. The hourly SETWMN is obtained by multiplying SETWMN by the hourly fractions used in the NSCWMN-th schedule.
CTRWMN	Humidistat lower set point control number (See Subsection 3.8)

Line 14: **DEADBT, DEADBW**

DEADBT Thermostat dead band [K]

DEADBW Humidistat dead band [kg/kg]

Line 15: **COLSNO, HETSNO**

COLSNO Cooling system number

HETSNO Heating system number

Use COLSNO and HETSNO, respectively, to indicate the mechanical cooling and heating systems used in simulations. Several types of mechanical cooling and heating systems can be simulated with the software. Use SUBROUTINE ZONEQP to define the performance of mechanical units. This subroutine may be modified to include their mechanical unit performance characteristics. (See Subsection 3.7) The cooling systems are available in the mechanical unit library under Subroutine ZONEQP.

COLSNO Enter 1 to activate a simplified constant capacity mechanical unit. This unit requires a total capacity (CONST(11) and a sensible heat fraction (CONST(15) as input. If the CONST(11) is set to a very large number such that QMACS (CONST(11) time CONST(15) evaluates to a value greater than 1.0E+20, then the mechanical unit will be assumed to have infinite power.

Whenever the zone temperature or the zone humidity ratio exceeds the cooling set points, the indoor conditions are brought to these set point values. (See Subsection 3.6, Lines 10 and 12) If QMACS evaluates to a number lower than 1.0E+20, the mechanical unit will behave as an actual air conditioner with only the thermostat controlling room conditions. A mechanical unit run time fraction is calculated and moisture is removed at a rate based on the value of sensible heat fraction subtracted from unity.(See Subsection 3.7)

COLSNO — Enter 1 to activate an actual mechanical unit. This mechanical unit is represented by a set of curve fit equations. This particular unit is obtained from the manufacture's data. The unit is assumed to be a function of the indoor and outdoor conditions.

Whenever the zone temperature exceeds the thermostat set point (See Subsection 3.6, Line 10), Subroutine ZONEQP is named. Depending upon the indoor and outdoor conditions sensible and latent power capacities of the unit are returned. If the capacity of the unit is greater than the required sensible load, the zone temperature is set to the thermostat set point. However, if the capacity is lower than the required sensible load, a new zone temperature is calculated using the available cooling power.

If COLSNO or HETSNO is set to zero, then the zone is assumed to float. In other words, no mechanical system is simulated.

Line 16: **RADFRC, QMASSS, QMASSL, NUMZON**

RADFRC — Use this variable to assign a portion (1-RADFRC) of the incoming solar radiation through transparent surfaces to the zone air. The remainder of RADFRC is equally distributed among the inside wall surfaces.

QMASSS — Use quick thermal mass factor to account for effective thermal capacitance of the zone air and furniture. This factor provides a method for describing a quick thermal mass having very large thermal conductivity that its temperature is essentially the same as the air temperature. If quick thermal mass is not used, set QMASSS to 0.

QMASSL — Use quick moisture mass factor to account for effective moisture capacitance of the zone air and furniture. This factor provides a method for describing a quick moisture mass having very large moisture diffusivity that is always in equilibrium with the room air conditions. If quick moisture mass is not used, set QMASSL to 0.

NUMZON — Zone source number. If NUMZON > 0, the program automatically calls Subroutine ZONSOR at Label NUMZON. The Subroutine lets user calculate mass flow rate caused by interzone mass flow from other zones and adds the extra terms in zone energy and moisture balance equations, or concentration equations for the particular zone. Detailed explanation is seen in Subsection 3.9.

Note: If the magnitude of the first input values of Lines 4 through 13 is not zero, then positive non-zero integer schedule numbers corresponding to schedule specification

(See Subsection 3.2) must be provided. If the value of load generation due to internal equipments is specified (CAPEQP = 0), then the equipment schedule number must be a non-zero positive integer number.

3.7 USER DEFINED MECHANICAL UNIT PERFORMANCE SPECIFICATION

You can define various primary and auxiliary mechanical cooling and heating systems. These systems are specified in SUBROUTINE ZONEQP. Subroutine ZONEQP is provided with these mathematical statements:

CALL ZONEQP (NGOTO, I, J, QMAC, QAUX)

NGOTO	Mechanical unit number from Subsection 3.6, Line 15
I	Zone equation number
J	Zone number
QMAC	Primary mechanical unit removal rate
QAUX	Auxiliary mechanical unit removal rate

Mathematical statements NGOTO, I, and J are input parameters, whereas the remainder are output parameters. If I=1, the units of QMAC and QAUX are [W]. If I=2, the units of QMAC and QAUX are [kg/s]. If I>2, QMAC and QAUX indicate concentration removal rate. The unit is dependent on the species equation. The data is provided to you through the common blocks. You may choose to use any of the data provided through these common blocks to define the performance of a unit. These are descriptions of the variables:

CP	Specific heat of air
DENSTY	Density of air
HFG	Heat of vaporization
IL	Integer vertical arrays (see array map)
XL	Real vertical arrays (see array map)

Note: You must not modify above values.

For example, Subroutine ZONEQP may appear as:

```
C     ##########################MECHANICAL UNIT#01
C     SIMPLIFIED CONSTANT CAPACITY MECHANICAL UNIT EXAMPLE
10    LOCN  = NCR(11)+MAXCON
      QMACS =  XL(LOCN+11)*XL(LCON+15)
      QMACL =  (1.0-XL(LOCN+15))*QMACS/HFG
      PMAC  =  1.0/XL(LOCN+16)*(QMACS+QMACL*HFG)
C
      QAUXS =  CONST(12)
      QAUXL =  CONST(13)
      PAUX  =  1.0/CONST(17)*(QAUXS+QAUXL*HFG)
C
      IF (I .EQ. 1) THEN
         QMAC = QMACS
         QAUX = QAUXS
      END IF
      IF (I .EQ. 2) THEN
         QMAC = QMACL
         QAUX = QAUXL
      END IF
C
      RETURN
```

where LOCN is location of constant in XL array. The example illustrates how a simplified constant capacity mechanical system can be modeled. QMACS represents the sensible capacity of the mechanical unit and is equated to XL(LOCN+11) (total system capacity) times XL(LOCN+15) (the sensible heat fraction for the unit). QMACL is the latent capacity of the unit and is equated to one minus the sensible heat fraction times QMACS divided by the heat of vaporization. The power requirement of the mechanical unit is calculated based on the coefficient of performance given in XL(LOCN+16). These variables represent the primary mechanical unit. The output of the example is dependent on the equation number I. If I=1, output is available sensible power. If I=2, output is available latent power.

To simulate a system of infinite QMACS is set larger than 1.0E+20. In this case, the program sets the zone condition to the values specified in the input, controlling an ideal machine with infinite capacity.

In all other cases where the capacity is not infinite, the mechanical unit is controlled by SETTMN and SETTMX and the sensible capacity of the machine (QMACS) is used to determine the primary mechanical unit run time based on the zone thermal loads as determined from the zone set points (SETTMX and SETTMN). The latent heat removal is a consequence of the sensible load and the mechanical unit performance parameters (XL(LOCN+11) and XL(LOCN+15)) and SETWMN and SETWMX are ignored.

The auxiliary mechanical unit provides a method of using more than one mechanical unit in the simulation. You may adapt it to perform whatever job is required of the backup system. This system is not activated unless the building load is greater than what can be provided by the primary unit. The auxiliary system can be used as the primary mechanical unit by setting the capacity of the primary unit [CONST(11) in the building input file] to zero.

3.8 USER DEFINED ROUTINES FOR THE BUILDINGS PROGRAM (CONTROL NUMBERS)

In Subsection 3.6, several control numbers are used for defining the input requirements for the zone. These control numbers are flags that identify the routines you define. The variables you are allowed to modify are listed in Table 3-2.

TABLE 3-2: Modifiable Variables for the Buildings Program

Symbol	Section	Line	Description
CAPEQP	3.6	4	Internal load generation due to equipment [W]
CAPFAN	3.6	5	Number of fans
CAPINF	3.6	6	Infiltration mass flow rate [ach]
CAPLGT	3.6	7	Internal load generation due to lighting [W]
CAPPEO	3.6	8	Internal load generation due to people [W]
CAPVEN	3.6	9	Ventilation mass flow rate [ach]
SETTMX	3.6	10	Thermostat upper set-point [K]
SETTMN	3.6	11	Thermostat lower set-point [K]
SETWMX	3.6	12	Humidistat upper set-point [kg/kg]
SETWMN	3.6	13	Humidistat lower set-point [kg/kg]

Subroutine ZONVRP in program module BILD.FOR is used for modifying the variables given in Table 3-2 on a run-time basis. Each variable used in Table 3-2 also has an associated control number. If you specify a positive non-zero integer for the control number, then the software assumes that the variables given in Table 3-2 are to be modified. If a minus or a zero control number is used, then no action is taken.

Subroutine ZONVRP has two mathematical statements which are CTRL and PROP. CTRL is the control number specified and it is an input in Subroutine ZONVRP. This subroutine is named only when the control number has a positive non-zero integer value. The control number is used as the index of the computed GO TO statement.

After entering, the subroutine control is transferred to the line labeled with the integer value of CTRL. Starting from this line you are allowed to define or modify the variables listed in Table 3-2. However, before exiting the subroutine, the modified variable must be equated to the output mathematical statement PROP. Several program variables are available for use in modifying these controlled variables. The program variables that are passed to ZONVRP for use in such calculations are given in Table 3-3. The variables given in Table 3-3 must never be modified here.

TABLE 3-3: Variables Available in the Buildings Program

Symbol	Description
XL(NCR(11)+MAXCON+I)	Constants defined in Section 3.1, Line 4
XL(NCR(2090)+I)	Environmental data (See Table 3-1)
CDAY	Current day number
CHOR	Hour of day ($1 \leq$ CHOR ≤ 24)
TSTP	Simulation time step (always in hours)
TINT	Simulation start time (always in hours)
TFIN	Simulation stop time (always in hours)
STIM	Simulation time [always in hours (TINT $\leq$ STIM $\leq$ TFIN)]
XL(NCR(2020)+I)	Zone volume
XL(NCR(2082)+I)	Zone temperature(s) at current time step
XL(NCR(2080)+I)	Zone temperature(s) at previous time step
XL(NCR(2082)+NOFZON+I)	Zone humidity ratio(s) at current time step
XL(NCR(2080)+NOFZON+I)	Zone humidity ratio(s) at previous time step

Example 1: Assume that a one-zone building is ventilated with a mass flow rate of 1.0 kg/s when the ambient temperature is less than 20°C but is not ventilated if the ambient temperature is greater than 20°C. In order to perform this simulation, the control number for CTRVEN (Subsection 3.6, Line 9) is set to +1 and Subroutine ZONVRP is modified as:

```
1       TAMB = XL(NCR(2090)+1)
C       PROP is initialized to zero for no vent case
        PROP = 0.0
C       PROP is equated to mass flow rate contained in
        CONST(2) for venting
        IF (TAMB .LE. CONST(1)) PROP=XL(NCR(11)+MAXCON+2)
        RETURN
```

Note: XL(NCR(2090)+1) contains the ambient drybulb temperature, XL(NCR(11)+MAXCON+1) contains the ventilation control temperature (293.15 K) and XL(NCR(11)+MAXCON+2) contains the ventilation mass flow rate (1.0 kg/s). After Subroutine ZONVRP is modified, program segment BILD.FOR must be successfully compiled and linked with the program segment FSEC.FOR.

Example 2: One form of the building infiltration rate is to be defined according to these equations:

$$Q = Q_b + (Q_w^2 + Q_s^2 + Q_u^2)^{\frac{1}{2}} \quad \textbf{(3-1)}$$

where,

$$Q_w = AV\beta C(1-R)^{\frac{1}{3}} \quad \textbf{(3-2)}$$

$$\beta = \frac{\alpha_w \left[\frac{H_w}{10}\right]^{qw}}{\alpha_t \left[\frac{H_t}{10}\right]^{gt}} \quad \textbf{(3-3)}$$

and,

$$Q_s = A\left[g\, h_s \left|\frac{\Delta T}{T}\right| \left(\frac{1+0.5R}{3}\right)^{\frac{1}{2}}\right] \left[\frac{1-X^2}{2-R}\right]^2 \quad \textbf{(3-4)}$$

These symbols and descriptions are used in Equations 3-1, 3-2, 3-3, 3-4:

Q	Total infiltration rate [m^3/s]
Q_w	Wind driven infiltration rate [m^3/s]
Q_s	Stack driven infiltration rate [m^3/s]
Q_b	Balanced infiltration rate [m^3/s]
Q_u	Unbalanced infiltration rate [m^3/s]
A	Total leakage area [m^2]
V	Local wind speed at ceiling height [m/s]
C	Local shielding coefficient [0.102-0.324; default 0.185]
R	Ratio of total ceiling and floor leakage to overall leakage [0-1; default 0.5]
g	Acceleration due to gravity [9.81 m/s^2]
ΔT	Indoor to outdoor temperature difference [K]
T	Indoor temperature [K]
X	Difference in fractional ceiling and floor leakage [0-1; default 0]
α	Alpha parameter for wind tower(w) or site (t) [0.47-1.30]
r	Gamma parameter for wind tower(w) or site (t) [0.10-1.00]
V	Wind speed at wind tower [m/s]
H_t	Height of building ceiling above grade [m]

In order to perform this simulation the control number for CTRINF (Subsection 3.6, Line 6) is set to +2 and Subroutine ZONVRP is modified as:

```
2       LOCN   =  NCR(11)+MAXCON    ! CONSTANT LOCATION
        LOCE   =  NCR(2090)         ! ENVIRONMENTAL LOCATION
        LOCT   =  NCR(2082)         ! ZONE TEMPERATURE LOCATION
        A      =  XL(LOCN+21)
        V      =  XL(LOCE+12)
        C      =  XL(LOCN+22)
        R      =  XL(LOCN+23)
        G      =  9.81
        HS     =  XL(LOCN+24)
        X      =  XL(LOCN+25)
        T      =  XL(LOCT+1)
        DT     =  T-XL(LOCE+1)
        QB     =  XL(LOCN+26)
        QU     =  XL(LOCN+27)
        ALW    =  XL(LOCN+28)
        HW     =  XL(LOCN+29)
        RW     =  XL(LOCN+30)
        ALT    =  XL(LOCN+31)
        HT     =  XL(LOCN+32)
        RT     =  XL(LOCN+33)
        BETA   =  (ALW*(HW/10)**GW)/(ALT*(HT/10)*GT)
C
        QW     =  A*V*BETA*C*(1-R)**0.33
        QS     =  A*(G*HS*ABS(DT/T)*(1+R/2)/3)**0.5*
       &           (1-X**2/(2-R)**2)
        DENSTY =   XL(LOCN+1)
        PROP   =  (QB+SQRT(QW**2+QS**2+QU**2))*DENSTY
        RETURN
```

3.9 USER DEFINED ROUTINE FOR THE LEAKAGE SOURCE OR SINK BETWEEN ZONES

This subroutine, **ZONSOR (NUMZON,SORSEN,SORLAT)**, is used to let user calculate mass flow rate caused by leakage between the zones and add extra terms in zone energy and moisture balance equations for this particular zone.

The zone source or sink number, NUMZON, is defined in Subsection 3.6, Line 17. When NUMZON is not equal to zero, the program will automatically call this subroutine and go to the corresponding label number, which is equal to NUMZON*10. SORSEN and SORLAT are output of the subroutine and convert zone mass flow rate into the corresponding zone sensible and latent loads.

For example, user can define that the building is composed of living zone (Zone 1), attic (Zone 2) and garage (Zone 3). There exists leakage mass flow rate, $\dot{m}$, between living zone and attic. In the building input file, the user may define NUMSOR=1 in Zone 1, and NUMZON=2 in Zone 2. The extra term in the energy and moisture balance equations, caused by leakage mass flow in the living zone, may be written as follows

$$\dot{m}C_p(T_2-T_1) \quad \text{and} \quad \dot{m}(W_2-W_1) \tag{3-5}$$

and extra terms in the attic energy and moisture balance equations may be written as below

$$\dot{m}C_p(T_1-T_2) \quad \text{and} \quad \dot{m}(W_1-W_2) \tag{3-6}$$

where

$\dot{m}$	Mass flow rate due to leakage [kg/s]
C_p	Specific heat [J/kg.K]
T_1	Lumped air temperature in the living zone [K]
T_2	Lumped air temperature in the attic [K]
W_1	Lumped air humidity ratio in the living zone [kg/kg]
W_2	Lumped air humidity ratio in the attic [kg/kg]

It should be noted that multi-zone mass flow rate may be determined by leakage area, pressure difference, etc. using other subroutine.

Let mass flow rate, $\dot{m}$, be defined as COFSOR in the subroutine. The modified program may be written as below

```
      SUBROUTINE ZONSOR (NUMSOR,SORSEN,SORLAT)
C     ##################################################
      Common block
      .
      .
C     ##################################################
      LOCV = NCR(2082)    ! ZONE VARIABLE LOCATION
      GOTO (10,20,30,40,50) NUMZON
C
10    SORSEN = COFSOR*CP*(XL(LOCV+2)-XL(LOCV+1))
      SORLAT = COFSOR*(XL(LOCV+NOFZON+2)-XL(LOCV+NOFZON+1))
      RETURN
C
20    SORSEN = COFSOR*CP*(XL(LOCV+1)-XL(LOCV+2))
      SORLAT = COFSOR*(XL(LOCV+NOFZON+1)-XL(LOCV+NOFZON+2))
      RETURN
```

where LOCV is defined as location of zone field variable in the current iteration. XL(LOCV+1), ..., XL(LOCV+NOFZON) indicate zone temperature, and XL(LOCV+NOFZON+1), ..., XL(LOCV+NOFZON+NOFZON) are zone humidity ratio. NOFZON is the number of simulated zones.

3.10 STRATIFIED AIR MODEL OF ATTIC THERMAL PERFORMANCE

This subsection shows how to use FSEC 3.0 effectively and modify the subroutine for specific problem. Interested user can refer to the references.

Attic thermal performance model developed by Parker et al. (1991) accounts for detailed inside surface radiation, buoyancy and wind driven air flows, and thermal stratification within the attic airspace by using FSEC 3.0. The attic air zone is divided into two lumped air spaces, lower and upper attic zones. The connection between two attic zones is buoyancy air flow.

The energy and moisture balance equations for both attic zones are written as follows

Lower attic energy balance

$$\rho V C_p \frac{\partial T_L}{\partial \tau} = \dot{m}_{buo} C_p (T_\alpha - T_L) + \sum h_j A_j (T^* - T_L) \qquad (3\text{-}7)$$

Lower attic moisture balance

$$\rho V \frac{\partial W_L}{\partial \tau} = \dot{m}_{buo} (W_\alpha - W_L) + \sum h_{m,j} A_j (W^* - W_L) \qquad (3\text{-}8)$$

Upper attic energy balance

$$\rho V C_p \frac{\partial T_U}{\partial \tau} = \dot{m}_{buo} C_p (T_L - T_U) + \sum h_j A_j (T^* - T_U) + \dot{m}_{inf} C_p (T_\alpha - T_U) \qquad (3\text{-}9)$$

Upper attic moisture balance

$$\rho V \frac{\partial W_U}{\partial \tau} = \dot{m}_{buo} (W_L - W_U) + \sum h_{m,j} A_j (W^* - W_U) + \dot{m}_{inf} (W_\alpha - W_U) \qquad (3\text{-}10)$$

where

A_j	Area of j-th surface exposed to corresponding zone
C_p	Specific heat
h_j	Convective heat transfer coefficient at j-th surface
$h_{m,j}$	Convective moisture transfer coefficient at j-th surface

$\dot{m}_{buo}$	Mass flow rate in the lower attic zone caused by buoyancy
$\dot{m}_{inf}$	Mass flow rate in the upper attic zone from the outside
T_L	Lower attic air temperature
T_U	Upper attic air temperature
T_α	Ambient attic air temperature
T^*	Inside surface temperature
W_L	Lower attic air humidity ratio
W_U	Upper attic air humidity ratio
W_α	Ambient attic air humidity ratio
W^*	Inside surface humidity ratio
V	Zone volume
ρ	Air density
τ	Time

It should be noted that the internal radiation energy exchange should be included in the attic thermal performance simulation. Due to the internal radiation exchange, the temperature of ceiling top surface is much higher than the air temperature of lower attic during day time. The use of night sky radiation calculation is also included for the deck surface temperature calculation at night. It is recommended that variable heat transfer coefficients are used in the attic thermal performance. For example, the heat transfer coefficient of outside surface is affected by ambient wind speed and direction, while heat transfer coefficient of inside surface is affected by temperature difference between zone air and inside surface. Obviously, iteration method should be used to obtained the converged values. The detailed description is referred to Parker et al. (1991).

Buoyancy mass flow rate may be formulated as

$$\dot{m}_{buo} = L_o \left[g H_s \frac{|T_d - T_\alpha|}{\min\{T_d, T_\alpha\}} \right] \qquad \textbf{(3-11)}$$

where

H_s	Height to neutral pressure plane
g	Acceleration due to gravity
L_o	Free inlet area
T_d	Deck surface temperature
T_α	Ambient temperature

The mass flow rate of wind driven ventilation

$$\dot{m}_{wind} = L_o C V^{*} \qquad (3\text{-}12)$$

where

C	Soffit discharge coefficient
V^{*}	Reduced wind speed

The air flow rate in the upper attic may be written as

$$\dot{m}_{inf} = R\,(\dot{m}_{buo}^{2} + \dot{m}_{wind}^{2})^{0.5} - \dot{m}_{buo} \qquad (3\text{-}13)$$

where R is increase in flow caused by excess of one opening over another. It should be pointed out that the unit of mass flow rate in the above equations is m^3/s.

The interzone mass flows of buoyancy and infiltration are calculated in the building subroutine ZONVRP at Labels 7 and 8 based on the above Eqs. (3-11) and (3-13).

```
      SUBROUTINE ZONVRP (NGOTO,PROP)
C     ######################################################
      GOTO (1,2,3,4,5,6,7,8,...) NGOTO
      ........
C     ############################ USER DEFINED ROUTINE <7>
7     DT = XL(NCR(2090)+1)-XL(NCR(510)+100)
      T  = DMIN1(XL(NCR(2090)+1),XL(NCR(510)+100))
      QB = 0.42*0.333*((9.81*0.6*DABS(DT)/T)**0.5)*DENSTY/
     &       XL(NCR(2021)+2)
      PROP = QB
      RETURN
C     ############################ USER DEFINED ROUTINE <8>
8     DT = XL(NCR(2090)+1)-XL(NCR(510)+100)
      T  = DMIN1(XL(NVR(2090)+1),XL(NCR(510)+100))
      QB = 0.42*0.333*((9.81*0.6*DABS(DT)/T)**0.5)*DENSTY/
     &       XL(NCR(2021)+2)
      V1 = 0.67*(10.0/10.0)**0.15/1.0/(3.0/10.0)**0.25*
     &       XL(NCR(2090)+11)
      QW = 660.96*XL(NCR(11)+MAXCON+67)*V1*DENSTY/3600.0/
     &       XL(NCR(2020)+2)
      PCT = 0.3733+1.0171*(1.0-EXP(-2.0))
      PROP = PCT*(QW*QW+QB*QB)**0.5-QB
      RETURN
      ......
```

where

QB	Buoyancy mass flow rate [$kg/m^3.s$]
QW	Wind driven mass flow rate [$kg/m^3.s$]
PCT	R defined in Eq. (3-13)
DENSTY	Air density [kg/m^3]

XL(NCR(2090)+1)	Ambient temperature [K]
XL(NCR(2090)+11)	Wind speed [m/s]
XL(NCR(510)+100)	Inside surface temperature of deck [K]
XL(NCR(2020)+2)	Lower attic volume [m^3]

It is worthwhile to note that the unit of mass flow rate used in the output of subroutine, $kg/m^3.s$, is required by FSEC 3.0.

In the FSEC 3.0 building program, the reference temperature and humidity ration of infiltration and ventilation is designed to be ambient temperature and humidity ratio. The reference temperature and humidity ratio of buoyancy terms in the upper attic energy and moisture balance equations are those of lower attic. Normal configuration of the program can not be used for the special term, $\dot{m}_{buo}C_p(T_L-T_U)$ and $\dot{m}_{buo}(W_L-W_U)$. The interzone air flow rate energy calculation is modified in the subroutine ZONSOR at Label 4. The program modification is shown as follows

```
      SUBROUTINE ZONSOR (NGOTO,SORSEN,SORLAT)
      .....
C     ########################################################
      GOTO (1,2,3,4,5,6,7,8,...) NGOTO
      ........
C     ###################### USER DEFINED SOURCE OR SINK <4>
      CALL ZONVRP (7,QU)     ! GET BUOYANCY MASS FLOW
      LOC = NCR(2020)+4      ! UPPER ATTIC VOLUME LOCATION
C
      SORSEN = QU*XL(LOC)*CP*(XL(NCR(2082)+2)-
     &           XL(NCR(2082)+4))
      SORLAT = QU*XL(LOC)*(XL(NCR(2082)+NOFZON+2)-
     &           XL(NCR(2082)+NOFZON+4))
      RETURN
      ......
```

where

XL(NCR(2082)+2)	Lower attic temperature [K]
XL(NCR(2082)+4)	Upper attic temperature [K]
XL(NCR(2082)+NOFZON+2)	Lower attic humidity ratio [kg/kg]
XL(NCR(2082)+NOFZON+4)	Upper attic humidity ratio [kg/kg]

The output terms of ZONSOR are added into zone energy and moisture balance equations.

3.11 CONDUCTION TRANSFER FUNCTION METHOD

Conduction Transfer Function method (CTF) (Stephenson & Mitalas, 1972 and Hittle, 1981) is used to calculate the surface temperature of multi-layer wall. It uses Laplace transform to transform heat conduction equation with respect to time first. Secondary, the second order ordinary differential equation is solved analytically by substituting boundary conditions. Finally, the solution is inverted by Laplace transform to obtain exact solution of heat conduction equation. CTF method is analytical solution and needs less computer time, compared with other approximated numerical methods, such as commonly used finite element method and finite difference method. The disadvantage is that thermal diffusivity should be restricted as constant and 1-D simulation is used for the time being. The variable heat transfer coefficient and internal radiation exchange cab be used by CTF. EMPD (Effective Moisture Penetration Depth) model (Keresteciogiu, 1990) for moisture transport in inside wall surface is also incorporated with CTF. When the user would like to use the theory of evaporation and condensation for detailed simulation of heat and moisture transport in the building, finite element method is only one choice for FSEC 3.0, since moisture diffusivity is not a constant and a function of temperature and moisture.

CTF is very useful for annual building simulation for less CPU time. When CTF method is used and the CTF flag is set to 1 in the FEM input file (see Section 2, Line 6), a particular input file is needed in addition to normal FEM and building input files. This particular input file required by CTF calculation may be created by FSEC 3.0 preprocessor. The input file format is list as follows

```
read ---> NOFWAL
do NW=1,NOFWAL
  read ---> NOFLAY
  do J=1,NOFLAY
    read ---> k,ρ,Cp,L
  end do
end do
```

where

NOFWAL	Number of walls
NOFLAY	Number of lays at i-th wall
k	Thermal conductivity at j-th layer [W/m.K]
ρ	Material density at j-th layer [kg/m^3]

C_p	Specific heat at j-th layer [J/kg.K]
L	Length of j-th layer [m]

It should noted that when CTF method is used in the build simulation, equation 10 has to be used in the FEM input file and FEM calculation will be bypassed. However, the node and element numbers from FEM input file will be kept in order to connect building program. In other words, the building program connection with FEM or CTF is based on node and element numbers provided by CTF or FEM. The program structure is the same for both numerical methods, FEM and CTF. Therefore, the calculation of CTF method uses the same input file of FEM to determine set of boundary conditions, heat transfer coefficients, ambient conditions and imposed heat fluxes, including solar radiation absorbed by external surface of the walls, etc. In other words, the FEM input file is still needed for CTF calculation.

CTF method provides the alternative method to calculate wall surface temperature in FSEC 3.0, although FEM method is main numerical method in the program. It should be noted that the frequency response method for inverse Laplace transform is used, instead of commonly used Z-transform.

3.12 SIMPLIFIED RADIATION INTERCHANGE ALGORITHM

It is not easy and quick to calculate view factors in the enclosure by entering coordinates of each wall and performing double integration. Mean Radiant Temperature (MRT) method (Walton, 1980) is an approximated method, which does not need to calculate view factors by double integral. By assuming that each surface is radiated to a fictitious surface which has an area, emissivity and temperature, the radiant interchange of each interior surface can be calculated.

The area of the fictitious surface is the summation of the areas of all other surfaces in the enclosure:

$$A_f = \sum_{j \neq i}^{n} A_j \qquad (3\text{-}14)$$

The emissivity is an area weighted average of all other surface emissivities:

$$\epsilon_f = \frac{\sum_{j \neq i}^{n} A_j \epsilon_j}{\sum_{j \neq i}^{n} A_j} \qquad (3\text{-}15)$$

The mean radiant temperature, T_f, seen by the i-th surface is

$$T_f = \frac{\sum_{j \neq i}^{n} A_j \epsilon_j T_j}{\sum_{j \neq i}^{n} A_j} \qquad (3\text{-}16)$$

The radiation interchange factor is

$$F_{i-f} = \frac{1.0}{1 + \frac{1-\epsilon_i}{\epsilon_i} + \frac{A_i(1-\epsilon_f)}{A_f\epsilon_f}} \qquad (3\text{-}17)$$

The radiant energy on i-th surface caused by internal radiation of all other surfaces is expressed as

$$R_i = \sigma F_{i-f}(T_f^4 - T_i^4) + r_{bal}$$

where r_{bal} is radiation balance handled by redistributing it equally on all surfaces to give conservation of energy and may be written as follows

$$r_{bal} = \frac{\sum_{i=1}^{n} \sigma F_{i-f}(T_f^4 - T_i^4) A_i}{\sum_{i=1}^{n} A_i} \qquad (3\text{-}19)$$

It should be noted that MRT method takes advantage without calculating view factors. It is good approximation in regular house structure. If the configuration of the enclosure is complicated, detailed view factor calculation is recommended. FSEC 3.0 does not provide view factor calculation for one dimensional building simulation for the time being. The user needs to calculate view factor first and then to create external unformatted input data file, referring to Appendix A **(VIWGET INPUT FILE)**.

SECTION 4

USER DEFINED ROUTINES, EQUATIONS, AND PROGRAMS

INTRODUCTION

This section describes User Defined Routines (UDRs), User Defined Equations (UDEs), and instructs you in their applications. UDRs and UDEs are governed by their respective subroutines, and their limits and options are discussed in detail. Definitions and examples are provided for clarity.

UDRs are used to model time and/or field variable dependent variables, and they are modeled through Subroutine VRPROP. The existing library equations can be modified and new equations can be added to the library by modifying Subroutine CONPAR. For UDRs and UDEs, Subroutines VRPROP and CONPAR must be properly modified, compiled, and linked with the main program.

Note: User Defined Programs are not automatized. Consult the FSEC staff for further information.

4.1 USER DEFINED ROUTINES

This subsection describes the software variables that are allowed to be modified in run time basis during simulation. These modifications can either be done globally or locally. Global modifications are performed at the beginning of a time step. For example, Subroutine VRPROP is retrieved at the beginning of a time step. The local modifications are performed on an element basis. For example, Subroutine VRPROP is retrieved for each element. Table 4-1 provides a list of modifiable variables. Examples of global and local modifications are given at the end of this subsection.

TABLE 4-1: Modifiable Software Variables

Symbol	Section	Line	Description
ILMP	2.1	3	Capacitance matrix type (global)
TSTP	2.1	3	Simulation time step (global)
THET	2.1	3	Time integration constant (global)
CON(I)	2.1	8-12	Constants used in UDR (global & local)
PRO(I)	2.4	3-7	Materials properties (local)
BCO(I)	2.5	3-6	Boundary condition set values (local)
PV(I)	2.6	2	Prescribed nodal unknowns (global)
VRG(I)	2.1	14-18	Global variables used in UDRs
VRL(I)	2.1	19-23	Local variables used in UDRs

It should be noted that the array in the FEM input file, such as CON(I), PRO(I), etc. are expressed in the corresponding vertical location of XL array in the program. Table 4-2 shows that the left column indicates the array names of input file and right column indicates expression used in the program.

Table 4-2: Array Names of Input File and Corresponding Address in the Program

Name	Location
CON(I)	XL(NCR(11)+I)
PRO(I)	XL(NCR(1502)+I)
BCO(I)	XL(NCR(1504)+I)
PV(I)	XL(NCR(0061)+I)
VRG(I)	XL(NCR(0013)+I)
VRL(I)	XL(NCR(0012)+I)

Use these procedures to modify the software variables:

1. Ensure that modifiable variables are a unique integer number which is represented by -(1000+NGOTO) in the input deck.

2. Define the modifiable variable in Subroutine VRPROP using the statement label NGOTO. Subroutine VRPROP is included in USER.FOR. (See Subsection 1.3)

3. Compile Subroutine VRPROP and link it with the main program. (See Subsection 1.3)

When a unique integer number represented by -(1000+NGOTO) is used for modified variables, the main program automatically retrieves Subroutine VRPROP. All modifications are done in this subroutine. You are required to perform these modifications.

Subroutine VRPROP is retrieved with a mathematical statement (PROP). When entering the subroutine, this mathematical statement has a value of -(1000+NGOTO) provided in the input deck. The value of NGOTO is calculated from the mathematical statement PROP as PROP+1000. With a computed GO TO statement, the control is transferred to the statement labelled with the number NGOTO. Perform modifications starting from this statement. When the modification of the variable is completed, the variable must be stored in PROP. Use the RETURN statement to exit from this subroutine. Upon returning from the VRPROP, the mathematical statement PROP contains the modified value for the defined variable.

Certain variables are passed to Subroutine VRPROP for you to use in the definition of modifiable variables. Table 4-3 provides a list of these variables.

Note: These values must not be changed or modified at any time.

TABLE 4-3: Software Variables Used in the Definition of Modifiable Variables at the Element Basis

Symbol or Location	Description
NCR(1750+1)+I	Nodal unknowns of Eq. 1 at current iteration [I=1,NON]
NCR(1750+2)+I	Nodal unknowns of Eq. 2 at current iteration [I=1,NON]
.	.....
NCR(1750+J)+I	Nodal unknowns of Eq. J at current iteration [I=1,NON]
.	.....
NCR(1750+250)+I	Nodal unknowns of Eq. 250 at current iteration [I=1,NON]
NCR(1750+1)+I	Nodal unknowns of Eq. 1 at previous iteration [I=NON+2,2*NON+1]
NCR(1750+2)+I	Nodal unknowns of Eq. 2 at previous iteration [I=NON+2,2*NON+1]
.	.....
NCR(1750+J)+I	Nodal unknowns of Eq. J at previous iteration [I=NON+2,2*NON+1]
.	.....
NCR(1750+250)+I	Nodal unknowns of Eq. 250 at previous iteration [I=NON+2,2*NON+1]
NCR(1750+1)+I	Integrated average of Eq. 1 at current iteration [I=NON+1]
NCR(1750+2)+I	Integrated average of Eq. 2 at current iteration [I=NON+1]
.	.....
NCR(1750+J)+I	Integrated average of Eq. 2 at current iteration [I=NON+1]

Table 4-3: Software Variables Used in the Definition of Modifiable Variables (continued)

Symbol or Location	Description
.	.....
NCR(1750+250)+I	Nodal unknowns of Eq. 250 at previous iteration [I=NON+1]
NCR(1750+1)+I	Integrated average of Eq. 1 at previous iteration [I=2*NON+2]
NCR(1750+2)+I	Integrated average of Eq. 1 at previous iteration [I=2*NON+2]
.	.....
NCR(1750+J)+I	Integrated average of Eq. J at previous iteration [I=2*NON+2]
.	.....
NCR(1750+250)+I	Integrated average of Eq. 250 at previous iteration [I=2*NON+2]
XL(NCR(11)+MAXCON+I)	Constants defined in Subsection 2.1, Lines 8-12
NN(I)	Nodal connectivity of the element
NON	Number of nodes for the element
STIM	Simulation time step
TFIN	Simulation stop time
TINT	Simulation start time
VOL	Volume of the element
XL(NCR(13)+I)	Global variables in 2.1, Lines 14-18
XL(NCR(12)+I)	Local variables in 2.1, Lines 19-23
XL(NCR(1501)+3*I-2)	Nodal x-coordinate of the element
XL(NCR(1501)+3*I-1)	Nodal y-coordinate of the element
XL(NCR(1501)+3*I)	Nodal z-coordinate of the element

Examples 1 through 4 illustrate the use of Subroutine VRPROP. The first example is a global modification. The other examples are local modifications.

Example 1: Simulation of variable time step (global).

In this example, the time step is increased depending upon the time elapsed. When 1/4th of the simulation is completed the time step is tripled, and when 3/4th is completed the time step is quadrupled.

Note: One of the Not Used constants defined in Subsection 2.1, Line 11, is used to define the original time step CON(40) [XL(NCR(11)+40)]. The TSTP value defined in Subsection 2.1, Line 3, is set to -1005.

```
5:      CON  = XL(NCR(11)+40)
        PROP = CON
        IF (STIM .GE. (0.25*TFIN+0.75*TINT)) PROP = CON*2.0
        IF (STIM .GE. (0.50*TFIN=0.50*TINT)) PROP = CON*3.0
        IF (STIM .GE. (0.75*TFIN+0.25*TINT)) PROP = CON*4.0
        RETURN
```

Example 2: Simulation of time dependent boundary condition (local).

This example simulates a sinusoidal convective fluid side temperature. This condition can be simulated by using -1006 for BCO(1) [XL(NCR(1504)+1)] in Subsection 2.5, Line 3. Three of the unused constants CON(41) [XL(NCR(11)+41)], CON(42) [XL(NCR(11)+42)], and CON(43) [XL(NCR(11)+43)] are used to represent number of cycles, average temperature, and amplitude, respectively.

```
6:      NOFC  = XL(NCR(11)+41)
        TAVG  = XL(NCR(11)+42)
        AMPL  = XL(NCR(11)+43)
        PI    = 4.0*ATAN(1.0)
        PROP  = TAVG+AMPL*SIN(PI*STIM*NOFC/12.0)
        RETURN
```

Example 3: Simulation of field variable dependent material property (local).

This example simulates a temperature dependent thermal conductivity defined by k=a+exp(b*T). In this equation, T corresponds to the integrated average element temperature. This simulation can be modeled by using -1007 for PRO(1) [XL(NCR(1502)+1)] in Subsection 2.4, Line 3. CON(44) [XL(NCR(11)+44)] and CON(45) [XL(NCR(11)+45)] are used to represent the a and b values used in the equation, respectively.

```
7:     PROP = XL(NCR(11)+44)+EXP(XL(NCR(11)+45)*
      &          XL(NCR(1760)+NON+1)
       RETURN
```

Example 4: Simulation of time and space variant variable (local).

This example simulates a time and position dependent point heat source. Initially, the source is located at x=0 and y=10. Afterward, the source moves parallel to x axis (y coordinate is always equal to 10) with a constant velocity of 0.01 m/s. The source also varies with time according to this equation. This condition can be simulated by using -1008 for PRO(10) [XL(NCR(1502)+10)] in Subsection 2.4, Line 3.

```
8:     YC = 10
       XC = XL(NCR(11)+46)*STIM
       X1 = XL(NCR(1501)+1*3-2)
       X4 = XL(NCR(1501)+4*3-2)
       Y1 = XL(NCR(1501)+1*3-1)
       Y2 = XL(NCR(1501)+2*3-1)
       IF (XC.LE.X1.AND.XC.GE.X4.AND.YC.GE.Y1.AND.YC.LE.Y2
       THEN
         PROP=XL(NCR(11)+47)+XL(NCR(11)+48)*STIM
       ELSE
        PROP=0.0
       END IF
```

Note: The algorithm in Example 4 is for an undistorted four node rectangular element. In CON(46) [XL(NCR(11)+46)] the velocity is stored, whereas in CON(47) [XL(NCR(11)+47)] and CON(48) [XL(NCR(11)+48)] the a and b coefficients are stored.

4.2 USER DEFINED OR MODIFIED EQUATIONS

This subsection describes the procedures for modifying existing library equations and adding new equations to the library. Equation modification and addition can be performed by modifying Subroutine CONPAR. In this version of the software, the modifications and additions are not handled automatically through the input deck because the governing equations and boundary conditions are not specified. You must perform the spatial discretization of the equations.

Note: These modifications and additions are best performed by someone who is familiar with the mathematics of finite element methods.

Use these steps to incorporate the modifications and additions to the equation library:

1. Define governing equation(s) with proper boundary conditions.

2. Observe spatial discretization of the governing equations and incorporation of the boundary conditions.

3. Select surface or volume integrations from the integration library for evaluating the elemental capacitance, stiffness matrices, and force vectors.

In the case of spatial discretization, the governing equation(s) is multiplied by weighing functions. Each term of the equation(s) is integrated over the volume of the element. The integration of higher order terms is reduced to lower order terms by the application of the Green-Gauss theorem. Boundary conditions of the 2nd and 3rd kind are applied at this stage. Next, the field variable(s) is substituted by its discrete definition ($T=Na$). These procedures are standard, and can be found in any finite element textbook. After spatial discretization, the original governing equation(s) is reduced to a time dependent ordinary differential equation(s) which is defined by Equation 4-1 and Equation 4-2.

For steady-state problems:

$$K_{ij}\, a_j = F_i \qquad \textbf{(4-1)}$$

For transient problems:

$$C_{ij}\, \dot{a}_j + K_{ij}\, a_j = F_i \qquad \textbf{(4-2)}$$

In Equation 4-1, $\dot{a}_j = 0$ for steady-state problems. In Equation 4-2, C denotes the capacitance matrix, K denotes the composite stiffness matrix, F denotes the force vector, $\dot{a}_j$ denotes the time derivative of the nodal unknowns, and a_j denotes the nodal unknown vector. Subscripts i and j are used to indicate the fundamental and cross terms, respectively. For transient problems, temporal discretization of Equation 4-2 is performed by the software using linear temporal weighing functions.

Equation 4-3 gives the Algebraic Finite Element Statement (AFES) used by the software to accommodate both spatial and temporal discretization.

$$(C_{ij}+\Theta\ K_{ij}\Delta\tau)\ a_j^{\tau+\Delta\tau} = \left[C_{ij}-(1-\Theta)\ K_{ij}\Delta\tau\right] a_j^{\tau} + (1-\Theta)f_i^{\tau}\ \Delta\tau + \Theta f_i^{\tau+\Delta\tau}\Delta\tau. \quad \textbf{(4-3)}$$

In Equation 4-3, Θ denotes the time integration constant, and $\Delta\tau$ denotes the time step. You should not be concerned with the solutions of Equation 4-1 or Equation 4-3. However, it is emphasized that C_{ij}, K_{ij}, and F_i represent the composite matrices and vectors. These composite matrices and vectors consist of a combination of several individual matrices and vectors that would result from spatial discretization.

Note: Equation 4-1 and Equation 4-3 are the AFES for steady-state and transient problems, respectively.

$$C_{ij}=\sum_{k=1}^{n} c_k\ ;\quad K_{ij} = \sum_{k=1}^{n} k_k\ ;\quad F_i = \sum_{k=1}^{n} f_k \quad \textbf{(4-4)}$$

The individual c_k, k_k, and f_k resulting from spatial discretization may be any of the forms in Equations 4-5 through 4-7.

$$c_k = \int_\Omega \{N^T | N_{,x}^T | N_{,y}^T | N_{,z}^T\} \text{ [constant] } \{N | N_{,x} | N_{,y} | N_{,z}\} \, d\Omega$$

(4-5)

$$k_k = \int_\Omega \{N^T | N_{,x}^T | N_{,y}^T | N_{,z}^T\} \text{ [constant] } \{N | N_{,x} | N_{,y} | N_{,z}\} \, d\Omega$$

$$k_k = \int_\Omega N^T \text{ [constant] } \{N | N_{,x} | N_{,y} | N_{,z}\} \{a_u | a_v | A_w | a_\psi\} \{N_{,x} | N_{,y} | N_{,z}\} \, d\Omega$$

$$k_k = \int_\Gamma \text{ [constant] } N \, d\Gamma$$

$$k_k = \int_\Gamma N^T \text{ [constant] } (Na_T)^3 \, N \, d\Gamma$$

(4-6)

$$f_k = \int_\Omega N^T \text{ [constant] } d\Omega$$

$$f_k = \int_\Gamma N^T \text{ [constant] } d\Gamma$$

(4-7)

Definition of equation terms:

a_T	Nodal temperature vector
a_u	Nodal velocity vector in x-direction
a_v	Nodal velocity vector in y-direction
a_w	Nodal velocity vector in z-direction
a_ψ	Nodal stream function vector
N	Shape function
$N_{,x}$	Partial derivative of the shape function in x direction
$N_{,y}$	Partial derivative of the shape function in y-direction
$N_{,z}$	Partial derivative of the shape function in z-direction
$\int_\Omega d\Omega$	Volume integration. For 1-D elements $d\Omega = A\ dl$, for 2-D elements $d\Omega = t\ dA$ where A is the area and t is the thickness of the element
$\int_\Gamma d\Gamma$	Surface integration. For 1-D elements $\int_\Gamma d\Gamma$ is replaced by the cross sectional area of the element

Equations 4-5 through 4-7 are given in the **Backus-Naur Form** (BNF). Choose only one of the magnitudes at a time that are within the braces and separated by vertical lines. The combinations that are currently supported by the software constitute the integral library and are provided in Table 4-3. If desired, new integrals can be added. The integrals shown in Table 4-3 are evaluated numerically using Gauss-Legendre quadrature. Specify the number of sampling points needed for the integration. The shape functions, $d\Omega$ and $d\Gamma$, are element dependent, and the software automatically accounts for it.

In the software, the different type of integrals are identified by variables written in the BNF notation. (See Figure 4-1)

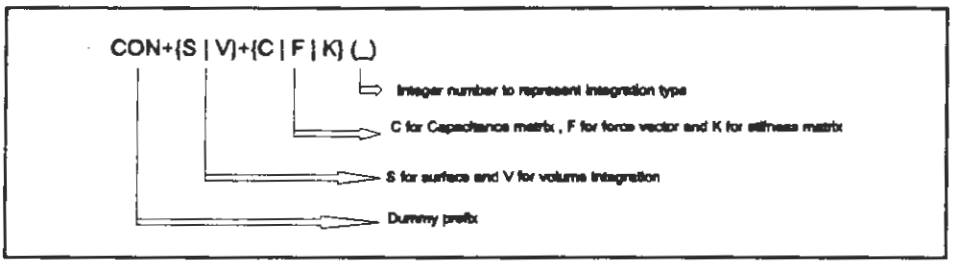

FIGURE 4-1: Conversion for Integration-Type Constants in CONPAR

In Table 4-3, the variable names are given within brackets and the integral type is given in the first column. If a non-zero magnitude is entered for the value contained within braces, the integral is automatically performed by the software.

Table 4-4: Different Integration Types

Number	Type of Numerical Integration
1.1	$\int_{\Omega} N^T \{CONVC\} N \, d\Omega$
1.2	$\int_{\Gamma} N^T \{CONSC\} N \, d\Gamma$
1.3	$\int_{\Omega} N^T \{CONVK\} N \, d\Omega$
2	$\int_{\Omega} N^T \{CONVK\} N \, a_u \, N_{,x} \, d\Omega$
3	$\int_{\Omega} N^T \{CONVK\} N \, a_v \, N_{,y} \, d\Omega$
4	$\int_{\Omega} N^T \{CONVK\} N \, a_w \, N_{,z} \, d\Omega$
5	$\int_{\Omega} N^T \{CONVK\} N_{,y} \, a_\psi \, N_{,x} \, d\Omega$
6	$\int_{\Omega} N^T \{CONVK\} N_{,x} \, a_\psi \, N_{,y} \, d\Omega$
7	$\int_{\Omega} N^T \{CONVK\} N_{,x} \, d\Omega$
8	$\int_{\Omega} N^T \{CONVK\} N_{,y} \, d\Omega$
9	$\int_{\Omega} N^T \{CONVK\} N_{,z} \, d\Omega$
10	$\int_{\Omega} N^T_{,x} \{CONVK\} N \, d\Omega$
11	$\int_{\Omega} N^T_{,x} \{CONVK\} N_{,x} \, d\Omega$
12	$\int_{\Omega} N^T_{,x} \{CONVK\} N_{,y} \, d\Omega$
13	$\int_{\Omega} N^T_{,x} \{CONVK\} N_{,z} \, d\Omega$
14	$\int_{\Omega} N^T_{,y} \{CONVK\} N \, d\Omega$
15	$\int_{\Omega} N^T_{,y} \{CONVK\} N_{,x} \, d\Omega$
16	$\int_{\Omega} N^T_{,y} \{CONVK\} N_{,y} \, d\Omega$
17	$\int_{\Omega} N^T_{,y} \{CONVK\} N_{,z} \, d\Omega$
18	$\int_{\Omega} N^T_{,z} \{CONVK\} N \, d\Omega$
19	$\int_{\Omega} N^T_{,z} \{CONVK\} N_{,x} \, d\Omega$
20	$\int_{\Omega} N^T_{,z} \{CONVK\} N_{,y} \, d\Omega$
21	$\int_{\Omega} N^T_{,z} \{CONVK\} N_{,z} \, d\Omega$
22	$\int_{\Omega} N^T \{CONVK\} N_{,x} \, a_u \, N_{,x} \, d\Omega$
23	$\int_{\Omega} N^T \{CONVK\} N_{,x} \, a_v \, N_{,x} \, d\Omega$
24	$\int_{\Omega} N^T \{CONVK\} N_{,x} \, a_w \, N_{,x} \, d\Omega$

Table 4-4: Different Integration Types (continued)

Number	Type of Numerical Integration
25	$\int_\Omega N^T \{CONVK\} N_{,x} a_u N_{,y} d\Omega$
26	$\int_\Omega N^T \{CONVK\} N_{,x} a_w N_{,z} d\Omega$
27	$\int_\Omega N^T \{CONVK\} N_{,y} a_u N_{,x} d\Omega$
28	$\int_\Omega N^T \{CONVK\} N_{,y} a_u N_{,y} d\Omega$
29	$\int_\Omega N^T \{CONVK\} N_{,y} a_v N_{,y} d\Omega$
30	$\int_\Omega N^T \{CONVK\} N_{,y} a_w N_{,y} d\Omega$
31	$\int_\Omega N^T \{CONVK\} N_{,z} a_v N_{,y} d\Omega$
32	$\int_\Omega N^T \{CONVK\} N_{,z} a_u N_{,z} d\Omega$
33	$\int_\Omega N^T \{CONVK\} N_{,z} a_v N_{,z} d\Omega$
34	$\int_\Omega N^T \{CONVK\} N_{,z} a_w N_{,z} d\Omega$
35	$\int_\Omega N^T_{,x} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,x} d\Omega$
36	$\int_\Omega N^T_{,x} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,y} d\Omega$
37	$\int_\Omega N^T_{,x} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,z} d\Omega$
38	$\int_\Omega N^T_{,y} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,x} d\Omega$
39	$\int_\Omega N^T_{,y} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,y} d\Omega$
40	$\int_\Omega N^T_{,y} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,z} d\Omega$
41	$\int_\Omega N^T_{,z} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,x} d\Omega$
42	$\int_\Omega N^T_{,z} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,y} d\Omega$
43	$\int_\Omega N^T_{,z} \{CONVK\} M d\Omega \ (\int_\Omega M^T M d\Omega)^{-1} \ \int_\Omega M^T N_{,z} d\Omega$
44	$\int_\Omega N^T \{CONVK\} N_{,x} a_p N_{,x} d\Omega$
45	$\int_\Omega N^T \{CONVK\} N_{,y} a_p N_{,y} d\Omega$
46	$\int_\Omega N^T \{CONVK\} N_{,z} a_p N_{,z} d\Omega$
47	$\int_\Omega N^T_{,x} \{CONVK\} N a_p N_{,x} d\Omega$
48	$\int_\Omega N^T_{,y} \{CONVK\} N a_p N_{,y} d\Omega$
49	$\int_\Omega N^T_{,z} \{CONVK\} N a_p N_{,z} d\Omega$
1.4	$\int_\Gamma N^T \{CONSK\} N d\Gamma$

Table 4-4: Different Integration Types (continued)

Number	Type of Numerical Integration
2.1	$\int_{\Gamma} N^T \{CONSK\} (Na_T)^3 N \, d\Gamma$
1.5	$\int_{\Omega} N^T \{CONVF\} \, d\Omega$
2.2	$\int_{\Omega} N^T_{,x} \{CONVF\} \, d\Omega$
3.1	$\int_{\Omega} N^T_{,y} \{CONVF\} \, d\Omega$
4.1	$\int_{\Omega} N^T_{,z} \{CONVF\} \, d\Omega$
1.6	$\int_{\Gamma} N^T \{CONSF\} \, d\Gamma$

Equation 4-8 and Equation 4-9 clarify the use of UDEs and modification of Subroutine CONPAR. If you want to solve this set of governing equations, select the geometry and boundary conditions from Figure 4-1, and enter them into the program. This process solves the set of equations.

$$a_1\frac{\partial T}{\partial \tau} + a_2\frac{\partial M}{\partial \tau} = a_3\frac{\partial^2 T}{\partial x^2} + a_4\frac{\partial^2 M}{\partial x^2} \quad \text{in} \quad \Omega \tag{4-8}$$

$$b_1\frac{\partial T}{\partial \tau} + b_2\frac{\partial M}{\partial \tau} = b_3\frac{\partial^2 T}{\partial x^2} + b_4\frac{\partial^2 M}{\partial x^2} \quad \text{in} \quad \Omega \tag{4-9}$$

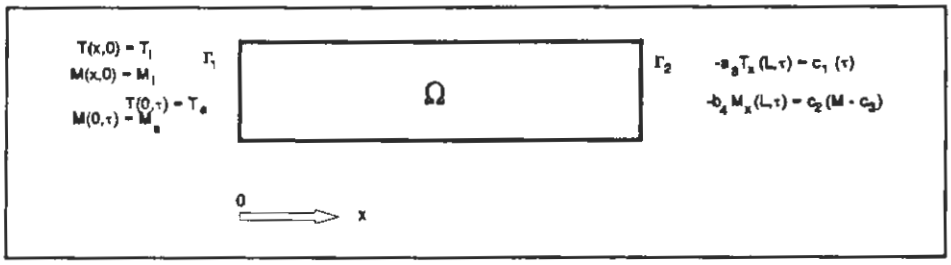

FIGURE 4-2: Schematic Definition of the Set of Equations

If the Galerkin Finite Element Method is used for spatial discretization, Equations 4-10 through 4-13 can be obtained.

$$C_{TT}\,\dot{a}_T + C_{TM}\,\dot{a}_M + K_{TT}\,a_T + K_{TM}\,a_M = F_T$$

$$C_{MT}\,\dot{a}_T + C_{MM}\,\dot{a}_M + K_{MT}\,a_T + K_{MM}\,a_M = F_M \qquad \textbf{(4-10)}$$

$$C_{TT} = \int_\Omega N^T \{a_1\}\, N\, d\Omega$$

$$C_{TM} = \int_\Omega N^T \{a_2\}\, N\, d\Omega$$

$$C_{MT} = \int_\Omega N^T \{b_1\}\, N\, d\Omega$$

$$C_{MM} = \int_\Omega N^T \{b_2\}\, N\, d\Omega \qquad \textbf{(4-11)}$$

$$K_{TT} = \int_{\Omega} N_{,x}^{T} \{a_3\} N_{,x} \, d\Omega$$

$$K_{TM} = \int_{\Omega} N_{,x}^{T} \{a_4\} N_{,x} \, d\Omega + \int_{\Gamma} N^{T} \left\{ \frac{a_4 c_2}{b_4} \right\} N \, d\Gamma$$

$$K_{MT} = \int_{\Omega} N_{,x}^{T} \{b_3\} N_{,x} \, d\Omega$$

$$K_{MM} = \int_{\Omega} N_{,x}^{T} \{b_4\} N_{,x} \, d\Omega + \int_{\Gamma} N^{T} \{c_2\} N \, d\Gamma$$

(4-12)

$$F_T = \int_{\Gamma} N^{T} \left\{ c_1 + \frac{a_4 c_2 c_3}{b_4} \right\} d\Gamma$$

$$F_M = \int_{\Gamma} N^{T} \left\{ c_2 c_3 + \frac{b_3 c_1}{a_3} \right\} d\Gamma$$

(4-13)

The constants used to define governing equations and boundary conditions can be entered through the input file. For this example application, use these input variables:

$$PRO(41) = a_1,\ PRO(42) = a_2,\ PRO(43) = a_3,\ PRO(44) = a_4$$

$$PRO(45) = b_1,\ PRO(46) = b_2,\ PRO(47) = b_3,\ PRO(48) = b_4$$

$$BCO(38) = c_1,\ BCO(39) = c_2,\ BCO(40) = c_3$$

Note: a_is' and b_is' must be treated as material properties. c_is' must be treated as boundary conditions. Input Subsections 2.4 and 2.5 are used for material property and boundary condition value specification, respectively. The above arrays, PRO and BCO shown in the input file, are expressed in XL arrays in the program as shown in Table 4.2.

If UDEs are solved in conjunction with existing library equations, only the unused entries of the NCR(1502) [PRO], NCR(1504) [BCO], and ncr(11) [CON] arrays should be used. Arrays NCR(13) [VRG] and NCR(12) [VRL] can be used freely. Equations 1 through 50 are reserved for library equations. Use Equations 51 through 250 for UDEs. If library equations are not used, then any equation number in conjunction to VRG and VRL arrays, PRO, BCO, and CON arrays can be safely used.

In this example, Equation 51 and Equation 52 are used to represent the UDEs. In these lines, the FORTRAN listing of modifications is provided. If you type these lines in Subroutine CONPAR, you will have the solutions to Equation 4-8 and Equation 4-9.

Note: In Subroutine CONPAR, NEQ and NEQS denote subscripts i and j of Equation 4-2.

MODIFICATION OF SUBROUTINE CONPAR

```
C     ##########################################################
      LOCB = NCR(1504)
      LOCP = NCR(1502)
      GOTO (10,20,.....,510,520,...) NGOTO
      .........
C     ########################################## EQUATION NUMBER 24
510   IF (NEQS .EQ. 51) THEN
         CONVC(01) = XL(LOCP+41)
         CONVK(11) = XL(LOCP+43)
         CONSF(01) = XL(LOCB+38)+XL(LOCP+44)*XL(LOCB+39)*
     &               XL(LOCB+40)/XL(LOCP+48)
      END IF
      IF (NEQS .EQ. 52) THEN
         CONVC(01) = XL(LOCP+42)
         CONVK(11) = XL(LOCP+44)
         CONSK(01) = XL(LOCP+44)*XL(LOCB+39)/XL(LOCP+48)
      END IF
      GO TO 2600
C     ##################################### EQUATION NUMBER 25
520   IF (NEQS .EQ. 51) THEN
         CONVC(01) = XL(LOCP+45)
         CONVK(11) = XL(LOCP+47)
      END IF
      IF (NEQS .EQ. 52) THEN
         CONVC(01) = XL(LOCP+46)
         CONVK(11) = XL(LOCP+48)
         CONSK(01) = XL(LOCB+39)
         CONSF(01) = XL(LOCB+39)*XL(LOCB+40)+XL(LOCP+47)*
     &               XL(LOCB+38)/XL(LOCP+43)
      END IF
      GO TO 2600
```

Note: Statement numbers 510 and 520 denote Equation 51 and Equation 52, respectively. Each equation description must be followed by GO TO 2600.

SECTION 5

LIBRARY EQUATIONS AND BOUNDARY CONDITIONS

INTRODUCTION

This section provides descriptions of library equations and boundary conditions. Library equations are existing equations contained within the software program. These equations can be modified according to the boundary conditions described in Section 4.

5.1 DOMAIN AND BOUNDARY DEFINITIONS

This subsection provides domain and boundary definitions for governing equations for various surfaces. Domain and surface definitions are illustrated in Figure 5-1. Different domains may be represented by the same governing equation. However, certain terms of the equation are not needed for each domain. The software automatically eliminates redundant terms when material properties are entered.

Use Table 5-1 for the relation between the library equations in Table 2-2 and the equation numbers from this section to mathematically represent each equation.

Table 5-1: Library Equation Numbers and Their Mathematical Formulations

Equation Number from Table 2-2	Subsection	Equation Number Used in Section 5
1,2,3	5.2	5-2
4	5.3	5-9
5	5.3	5-8
6	5.3	5-10
7	5.3	5-11
8	5.2	5-3
9	5.3	5-12
10,11	5.4	5-23
12	5.5	5-35
13,14	5.4	5-24
15	5.5	5-36
16	5.6	5-42
17	5.3	5-8
18,19	5.7	5-46
20,21	5.7	5-47
	5.8	5-49
25,26	5.9	5-74

In Figure 5-1, Ω_R denotes the lumped domain. Within this domain, the field variables are assumed to be spatially invariant and are allowed to vary in time. The solution to this domain can be obtained, based on the defined variables in the program.

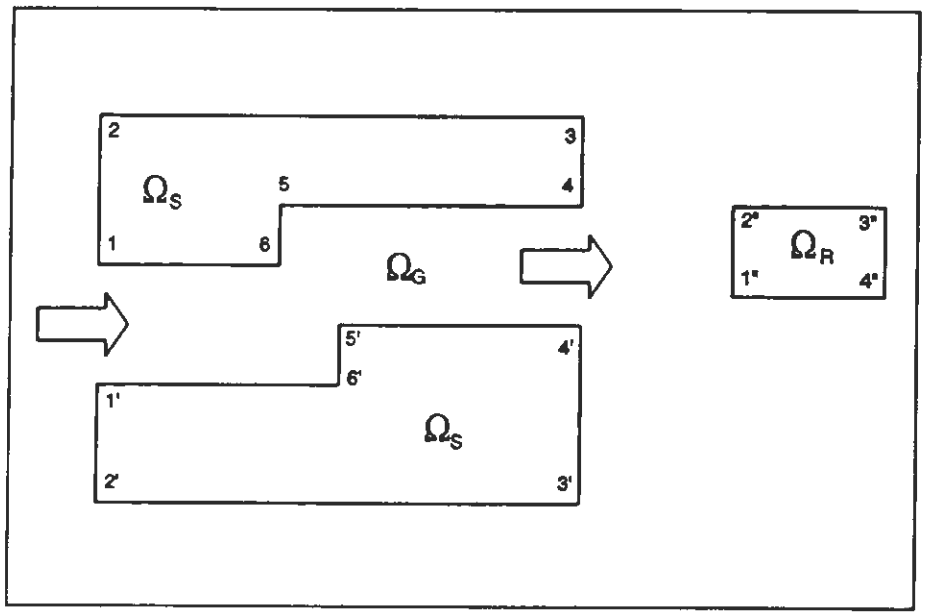

Figure 5-1: Domain and Surface Definitions

Table 5-2 defines typical boundary conditions and symbols for different boundaries.

Table 5-2: Typical Boundary Conditions

Boundary	Symbol	Surface Definitions
1-1'	Γ_i	Inflow boundary conditions
4-4'	Γ_o	Outflow boundary conditions
1-2-3-4	Γ_α	Ambient boundary conditions for solid domains
1'-2'-3'-4'	Γ_α	Ambient boundary conditions for solid domains
1-6-5-4	$\Gamma_{S\text{-}G}$	Solid-gas interface boundary conditions
1'-6'-5'-4'	$\Gamma_{S\text{-}G}$	Interface boundary conditions
1"-2"-3"-4"	Γ_R	Lumped and distributed equation interface

5.2 FLUID FLOW EQUATIONS IN PRIMITIVE VARIABLES

Governing Equations

These are equations for fluid flow in primitive variables.

Conservation of mass

$$u_{j,j} = 0 \quad \text{in } \Omega_G \tag{5-1}$$

Conservation of momentum

$$\rho \left[\frac{\partial u_i}{\partial \tau} + u_j\, u_{i,j} \right] = -p_{,i} + \rho g_i \left[1 - \beta_T (T - T_o) - \beta_M (\rho_v - \rho_{v,o}) - \beta_C (C - C_o) \right] + \mu_e \left[u_{i,j} + u_{j,i} \right]_{,j} + \frac{2}{3} \rho \kappa_{,i} \quad \text{in } \Omega_G \tag{5-2}$$

Use the Penalty Finite Element Method (PFEM) to solve the fluid flow equations in primitive variables, Equation 5-1 is replaced by this equation:

$$\bar{\epsilon}\,(u_{j,j}) = -p \quad \text{in } \Omega_G \tag{5-3}$$

In Equation 5-3, ϵ denotes the penalty parameter. (See Subsection 2.1, Line 11) Equation 5-3 eliminates the pressure term to obtain the solution of Equation 5-2. If Library Equations 1, 2, and 3 are solved, only the velocity field will be obtained. Solve Library Equation 8 to obtain the pressure distribution.

Properties

$$\mu_e = \begin{cases} \mu \text{ in } \Omega_G \text{ for laminar flow} \\ \mu+\mu_T \text{ in } \Omega_G \text{ for turbulent flow} \end{cases} \tag{5-4}$$

For turbulent flow simulations the dynamic viscosity, μ, is replaced by $\mu+\mu_T$. Set the laminar flow simulations $2/3\rho\kappa_{,i}$ to zero.

Boundary Conditions

These are boundary conditions for fluid flow equations in primitive variables:

$$u_i = u_i(x_1,x_2,x_3,\tau,V,\ldots) \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{S\text{-}G}$$

$$u_{,i}\cdot n = 0 \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{S\text{-}G} \tag{5-5}$$

5.3 VORTICITY AND STREAM FUNCTION EQUATIONS

The software analyzes fluid flow using vorticity and stream function formulas.

If, velocities are related to the stream function through these equations,

$$u_1 = \frac{\partial \psi}{\partial x_2} \quad \text{and} \quad u_2 = -\frac{\partial \psi}{\partial x_1} \quad \text{in } \Omega_G \tag{5-6}$$

and, the vorticity is defined by this equation,

$$\omega = \frac{\partial u_2}{\partial x_1} - \frac{\partial u_1}{\partial x_2} \quad \text{in } \Omega_G \tag{5-7}$$

then, Equations 5-1 and 5-2 can be replaced by these equations:

$$\rho \left[\frac{\partial \omega}{\partial \tau} + u_j \omega_j \right] = (\mu_e \omega_j)_j + \rho g_1 \left[\beta_T \frac{\partial T}{\partial x_2} + \beta_M \frac{\partial \rho_v}{\partial x_2} + \beta_C \frac{\partial C}{\partial x_2} \right] - \rho g_2 \left[\beta_T \frac{\partial T}{\partial x_1} + \beta_M \frac{\partial \rho_v}{\partial x_1} + \beta_C \frac{\partial C}{\partial x_1} \right] \quad \text{in } \Omega_G \tag{5-8}$$

$$(\psi_j)_j = -\omega \quad \text{in } \Omega_G \tag{5-9}$$

Equation 5-8 represents stream function equations and Equation 5-9 represents vorticity equations. Obtain the solutions to these equations by solving Library Equation 4 and Library Equation 5. If potential flow is simulated, only Library Equation 4 needs to be solved.

Relate the velocity field to the vorticity field with these equations:

$$(u_{1,j})_{,j} = -\frac{\partial \omega}{\partial x_2} \quad \text{in } \Omega_G \tag{5-10}$$

$$(u_{2,j})_{,j} = +\frac{\partial \omega}{\partial x_1} \quad \text{in } \Omega_G \tag{5-11}$$

If vorticity and stream function equations are used, then the velocities are calculated at the element centroids. To calculate the velocities at the nodal points, Library Equation 6 and Library Equation 7 need to be used in conjunction with Equation 4 and Equation 5. Pressure is eliminated in the vorticity and stream function formulations. Equation 5-12 corresponds to Library Equation 9. This equation recovers the pressure field:

$$\frac{\partial^2 p}{\partial x_1^2} + \frac{\partial^2 p}{\partial x_2^2} = 2\rho \left[\frac{\partial u_1}{\partial x_1}\frac{\partial u_2}{\partial x_2} - \frac{\partial u_1}{\partial x_2}\frac{\partial u_2}{\partial x_1} \right]$$

$$= 2\rho \left[\frac{\partial^2 \psi}{\partial x_1^2}\frac{\partial \psi^2}{\partial x_2^2} - \left(\frac{\partial^2 \psi}{\partial x_1 \partial x_2} \right)^2 \right] \tag{5-12}$$

Properties

Use this equation for vorticity and stream functions:

$$\mu_e = \begin{cases} \mu \text{ in } \Omega_G \text{ for laminar flow} \\ \mu+\mu_T \text{ in } \Omega_G \text{ for turbulent flow} \end{cases}$$

(5-13)

Boundary Conditions

These are the boundary conditions for vorticity and stream function equations:

$$\nabla\psi = U\ \nabla n \quad \text{on } \Gamma_i$$

(5-14)

$$\psi_j \cdot n = 0 \quad \text{on } \Gamma_o$$

(5-15)

$$\omega_j \cdot n = 0 \quad \text{on } \Gamma_o$$

(5-16)

$$\psi = \psi(x_1, x_2, \tau, V, \ldots) \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{S\text{-}G} \tag{5-17}$$

$$\omega = \omega(x_1, x_2, \tau, V, \ldots) \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{S\text{-}G} \tag{5-18}$$

$$\omega = \frac{\partial u_2}{\partial x_1}\frac{\partial u_1}{\partial x_2} \quad \text{on } \Gamma_i \tag{5-19}$$

$$\omega = \frac{\partial^2 \psi}{\partial n^2} \quad \text{on } \Gamma_{S\text{-}G} \tag{5-20}$$

Two different wall-vorticity boundary conditions are used:
(See Subsection 2.1, Line 5)

$$\omega^n = \frac{2(\psi^n - \psi^{n+1} + U_o \Delta n)}{(\Delta n)^2} \tag{5-21}$$

$$\omega^n = \frac{7\omega^n - 8\omega^{n+1} + \omega^{n+2}}{(\Delta n)^2} \tag{5-22}$$

5.4 HEAT AND MOISTURE TRANSFER EQUATIONS, EVAPORATION/CONDENSATION THEORY

This subsection provides the combined heat and moisture equations using the evaporation and condensation theory. These are the governing equations:

$$\left[(\rho\ C_p)_c + \lambda\rho_b B_\rho\right]\left[\frac{\partial T}{\partial \tau} + u_j T_{,j}\right] = \left[kT_{,j}\right]_{,j} + \mu\Phi + Q_T + \lambda\rho_b A_T \frac{\partial \rho_v}{\partial \tau} \quad \text{in } \Omega_G \text{ and } \Omega_S \tag{5-23}$$

$$\left(\Lambda + \rho_b A_T\right)\left[\frac{\partial \rho_v}{\partial \tau} + u_j \rho_{v,j}\right] = \left[\Lambda D_{v,c}\ \rho_{v,j}\right]_{,j} + Q_M + \rho_b B_\rho \frac{\partial T}{\partial \tau} \quad \text{in } \Omega_G \text{ and } \Omega_S \tag{5-24}$$

In Equation 5-23, Φ denotes the dissipation function and is solved in this equation:

$$\Phi = \left(\frac{\partial u_1}{\partial x_1}\right)^2 + \left(\frac{\partial u_2}{\partial x_2}\right)^2 + \left(\frac{\partial u_3}{\partial x_3}\right)^2 + \left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\right)^2 + \left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right)^2 + \left(\frac{\partial u_3}{\partial x_1} + \frac{\partial u_1}{\partial x_3}\right)^2 \tag{5-25}$$

Equation 5-23 and Equation 5-24 can be solved in various combinations. Table 5-3 describes these combinations. The library equation numbers in Table 5-3 are defined in Section 2, Table 2-2.

Table 5-3: Equation Combinations for Heat and Mass Transfer Simulations

Equations		Flow Type			Variables		Library Equation Numbers
Heat	Mass	Potential	Laminar	Turbulent	ψ-ω	u_i	
X							10
X		X			X		4,11
X			X		X		4,5,11
X			X			X	1,2,3,10
X				X	X		4,5,6,7, 11,19,21
X				X		X	1,2,3,10,18, 20
X	X						10,13
X	X	X			X		4,11,14
X	X		X		X		4,5,11,14
X	X		X			X	1,2,3,10,13
X	X			X	X		4,5,6,7,11, 14,19, 21
X	X			X		X	1,2,3,10,13, 18,20

Properties

The equilibrium moisture content curve is simulated by the following equation where ϕ is the relative humidity and U_e is the equilibrium moisture content of the material:

$$U_e = a\phi^b + c\phi^d \quad \text{in } \Omega_G \text{ and } \Omega_S$$

$$a=0;\quad b=0;\quad c=0;\quad d=0; \quad \text{in } \Omega_G$$

$$a \geq 0;\quad b \geq 0;\quad c \geq 0;\quad d \geq 0 \quad \text{in } \Omega_S$$

(5-26)

In Equation 5-26, a, b, c, and d denote the empirical constants. For laminar and turbulent flows, the thermal conductivity and mass diffusivities are simulated throughout these equations:

$$k_e = \begin{cases} k(T,\rho_v) \text{ in } \Omega_G \text{ for laminar flow} \\ k(T,\rho_v) + \dfrac{C_p \mu_T}{\sigma_T} \text{ in } \Omega_G \text{ for turbulent flow} \end{cases}$$

(5-27)

$$D_{v,e} = \begin{cases} D_a \text{ in } \Omega_G \text{ for laminar flow} \\ D_a + \dfrac{\mu_T}{\rho \sigma_T} \text{ in } \Omega_G \text{ for turbulent flow} \end{cases}$$

(5-28)

Vapor diffusivity of the solid material is related to the molecular diffusivity of water vapor in air through this equation:

$$D_v = \frac{D_a P}{\tau_o (P - P_v)} \quad \text{in } \Omega_G \text{ and } \Omega_S \tag{5-29}$$

Molecular diffusivity of water vapor in air is represented by this equation:

$$D_a = \frac{9.26 \times 10^{-4} T^{2.5}}{P (T+245)} \quad \text{in } \Omega_G \text{ and } \Omega_S \tag{5-30}$$

Boundary Conditions

These are the boundary conditions for heat moisture transfer equations and the evaporation/condensation theory:

$$-k_e T_{,j} = \begin{cases} -q''_T + h_T(T^* - T_\alpha) + \epsilon\sigma F_s(T^{*4} - T_s^4) \\ \qquad + \sum_{j=1}^{nor} \sigma F_{i-j}(T^{*4} - T_j^4) \quad \text{on } \Gamma_\alpha \\ -q''_T + h_T(T^* - T_R) + \epsilon\sigma F_s(T^{*4} - T_s^4) \\ \qquad + \sum_{j=1}^{nor} \sigma F_{i-j}(T^{*4} - T_j^4) \quad \text{on } \Gamma_R \end{cases} \tag{5-31}$$

$$-\Lambda D_{v,e}\rho_{v_{,j}} = \begin{cases} -q''_M + h_M(\rho_v^* - \rho_{v_\alpha}) \quad \text{on } \Gamma_\alpha \\ -q''_M + h_M(\rho_v^* - \rho_{v_s}) \quad \text{on } \Gamma_R \end{cases} \tag{5-32}$$

$$T = T(x_1, x_2, x_3, \tau, V, \ldots) \quad \text{on any } \Gamma \tag{5-33}$$

$$\rho_v = \rho_v(x_1, x_2, x_3, \tau, V, \ldots) \quad \text{on any } \Gamma \tag{5-34}$$

5.5 HEAT AND MOISTURE TRANSFER EQUATIONS, LUIKOV'S THEORY

Governing Equations

These governing equations combine heat and mass transfer equations for Luikov's theory:

$$(\rho\ C_p)_e \frac{\partial T}{\partial \tau} = (K_{11}T_{,j})_{,j} + (K_{12}M_{,j})_{,j} + Q_T \quad \text{in } \Omega_s$$

(5-35)

$$\rho_e C_M \frac{\partial M}{\partial \tau} = (K_{21}T_{,j})_{,j} + (K_{22}M_{,j})_{,j} + Q_M \quad \text{in } \Omega_s$$

(5-36)

Properties

In Equation 5-35 and Equation 5-36, K_{ij}s' denotes kinetic coefficients.

$$K_{11} = k_e + \gamma\lambda k_M\delta$$

$$K_{12} = \gamma\lambda k_M$$

$$K_{21} = k_M\delta$$

$$K_{22} = k_M$$

(5-37)

Luikov's equations are simulated by using Equation 12 and Equation 15.

Note: Do not solve Luikov's equations with fluid flow equations.

Boundary Conditions

These are the boundary conditions for heat and moisture transfer equations and Luikov's theory:

$$-K_{11}T_j - K_{12}M_j = \begin{cases} -q''_T + h_T(T^* - T_\alpha) + \epsilon\sigma F_s(T^{*4} - T_s^4) + \lambda h_{M,M}(M^* - M_\alpha) \\ \qquad -\gamma\lambda q''_M + \sum_{j=1}^{nor} \sigma F_{i-j}(T^{*4} - T_j^4) \quad \text{on } \Gamma_\alpha \\ -q''_T + h_T(T^* - T_R) + \epsilon\sigma F_s(T^{*4} - T_s^4) + \lambda h_{M,M}(M^* - M_R) \\ \qquad -\gamma\lambda q''_M + \sum_{j=1}^{nor} \sigma F_{i-j}(T^{*4} - T_j^4) \quad \text{on } \Gamma_R \end{cases}$$

(5-38)

$$-K_{21}T_j - K_{22}M_j = \begin{cases} -q''_M + h_{M,M}(M^* - M_\alpha) & \text{on } \Gamma_\alpha \\ -q''_M + h_{M,M}(M^* - M_R) & \text{on } \Gamma_R \end{cases}$$

(5-39)

$$T = T(x_1, x_2, x_3, \tau, V, \ldots) \quad \text{on any } \Gamma$$

(5-40)

$$M = M(x_1, x_2, x_3, \tau, V, \ldots) \quad \text{on any } \Gamma$$

(5-41)

5.6 CONTAMINANT DISTRIBUTION EQUATION

Governing Equations

The contaminant distribution is simulated in this equation:

$$\frac{\partial C}{\partial \tau} + u_j C_{,j} = \left[D_{c,e} C_{,j}\right]_{,j} + Q_C \quad \text{in } \Omega_G. \tag{5-42}$$

Illustrated in Table 5-4 are various combinations used to solve Equation 5-42.

Table 5-4: Equation Combinations for Contaminant Distribution Simulations

Flow Type			Variables		Library Equation Numbers
Potential	Laminar	Turbulent	ψ-ω	u_i	
					16
X			X		4,17
	X		X		4,5,17
	X			X	1,2,3,16
		X	X		4,5,6,7,17,19,21
		X		X	1,2,3,16,18,20

Properties

The contaminant diffusivities for laminar and turbulent flows are simulated in these equations:

$$D_{c,e} = \begin{cases} D_c \text{ in } \Omega_G \text{ for laminar flow} \\ D_c + \dfrac{\mu_T}{\rho \sigma_c} \text{ in } \Omega_G \text{ for turbulent flow} \end{cases}$$

(5-43)

Boundary Conditions

These are the boundary conditions for contaminant distribution equations:

$$-D_{c,e}C_{,j} = \begin{cases} -q''_C + h_C(C^* - C_\alpha) & \text{on } \Gamma_\alpha \\ -q''_C + h_C(C^* - C_R) & \text{on } \Gamma_R \end{cases}$$

(5-44)

$$C = C(x_1, x_2, x_3, \tau, V, \ldots) \quad \text{on any } \Gamma$$

(5-45)

5.7 TURBULENCE EQUATION κ-ϵ MODEL

Governing Equations

Governing equations for the κ-ϵ turbulence model are defined by these equations:

$$\rho\left(\frac{\partial \kappa}{\partial \tau} + u_j \kappa_{,j}\right) = + \left(\frac{\mu_T}{\sigma_\kappa}\kappa_{,j}\right)_{,j} + \mu_T \Phi - \rho\epsilon$$
$$- \mu_T g_i \left(\frac{\beta_T}{\sigma_T} T_{,j} + \frac{\beta_M}{\sigma_M}\rho_{v,j} + \frac{\beta_C}{\sigma_C} C_{,j}\right) \quad \text{in } \Omega_G$$

(5-46)

$$\rho\left(\frac{\partial \epsilon}{\partial \tau} + u_j \epsilon_{,j}\right) = + \left(\frac{\mu_T}{\sigma_\epsilon}\epsilon_{,j}\right)_{,j} + C_1 \mu_T \Phi \frac{\epsilon}{\kappa} - \rho C_2 \frac{\epsilon^2}{\kappa}$$
$$+ C_1(1-C_3)\frac{\epsilon}{\kappa}\mu_T g_i \left(\frac{\beta_T}{\sigma_T} T_{,j} + \frac{\beta_M}{\sigma_M}\rho_{v,j} + \frac{\beta_C}{\sigma_C} C_{,j}\right) \quad \text{in } \Omega_G$$

(5-47)

Properties

The turbulent eddy viscosity, μ_T, is used in this equation:

$$\mu_T = \rho C_\mu \frac{\kappa^2}{\epsilon} \quad \text{in } \Omega_G$$

(5-48)

Use empirical constants in Equation 5-46, Equation 5-47, and Equation 5-48. These equations can be changed through the input file.

$$\sigma_C = 0.90 \quad \sigma_M = 0.90 \quad \sigma_T = 0.90 \quad \sigma_\epsilon = 1.25 \quad \sigma_\kappa = 1.00$$

$$C_\mu = 0.09 \quad C_1 = 1.44 \quad C_2 = 1.92 \quad C_3 = 0.80$$

Boundary Conditions

The specification of the boundary conditions used in the κ-ϵ turbulence model are important and can be used in several different ways.

Note: The software does not provide any library boundary conditions for this model. To provide the boundary condition equations, such as wall functions, follow procedures outlined in Section 4.

5.8 MULTI-PHASE FLOW OF IMMISCIBLE FLUIDS AND TRANSPORT OF NONREACTIVE SUBSTANCES

Governing Equations

These equations are valid for both porous and fractured mediums. The velocity vector for each phase (U_i^α) are defined by Darcy's law.

$$U_i^\alpha = -\frac{k_{ij}^\alpha}{\mu^\alpha}\left(P_J^\alpha + \rho^\alpha g z_{,j}\right) \qquad \textbf{(5-49)}$$

Write (h^α-z) < 2000 m and incompressible flow pressure and elevation in terms of hydraulic head (h):

$$P_j^\alpha + \rho^\alpha g z_{,j} = \rho^\alpha g \left[\frac{P^\alpha}{\rho^\alpha g} + z \right]_{,j} = \rho^\alpha g h_j^\alpha \tag{5-50}$$

Write the continuity equation for each phase:

$$\left(\phi S^\alpha \rho^\alpha\right)_{,\tau} + \left(\rho^\alpha U_j^\alpha\right)_{,j} = Q^\alpha$$

$$\left(\phi s^\alpha \rho^\alpha\right)_{,\tau} + \left[-\rho^\alpha \frac{k_{ij}^\alpha}{\mu^\alpha} \left(P_{,j}^\alpha + \rho^\alpha g z_{,j} \right) \right]_{,j} = Q^\alpha \tag{5-51}$$

For incompressible flows, the fluid density of each phase (ρ^α) is treated as constant. For compressible flows, fluid density for each phase is calculated through these equations:

$$\rho^\alpha = \begin{cases} \rho_o e^{\beta_L^\alpha (P^\alpha - P_o^\alpha)} & \text{for liquid} \\ \dfrac{m^\alpha P^\alpha}{R T^\alpha Z^\alpha} & \text{for real gases} \end{cases} \tag{5-52}$$

The volumetric saturation for each of the fluids, S^α = part of porosity occupied by fluid α/total porosity, is related to capillary pressure through empirical equations:

$$S^\alpha = S^\alpha(P_c^\alpha) \tag{5-53}$$

Equation 5-54 defines the capillary pressure (P_c^α):

$$P_c^\alpha = P^i - P^j \tag{5-54}$$

Relations between saturations:

$$\sum_{\alpha=1}^{nop} S^\alpha = 1 \tag{5-55}$$

The rate of change of porosity with rate of change in pressure is shown in these equations:

$$\phi_{,T} = (\alpha - \alpha_s)\, P_{,\tau}$$

(5-56)

$$P^{\alpha} = \rho^{\alpha} g(h^{\alpha} - z) = P^{\alpha}(x_1, x_2, x_3, \tau, V, \ldots)$$

$$-\frac{k_{ij}^{\alpha}}{\mu^{\alpha}}(P^{\alpha}{}_{,j} + \rho^{\alpha} g z_{,j}) = q^{\alpha}$$

(5-57)

Mass conservation equation for solutes (η) in a multi-phase system (α):

$$\sum_{\alpha=1}^{nop} (\phi S^{\alpha} C_{\eta}^{\alpha})_{,\tau} + \sum_{\alpha=1}^{nop} (c_{\eta}^{\alpha} U_i^{\alpha})_{,j} = \sum_{\alpha=1}^{nop} (\phi S^{\alpha} D_{ij}^{\alpha} c_{\eta,j}^{\alpha})_{,i} + Q_{\eta}$$

$$\sum_{\alpha=1}^{nop} (\phi S^{\alpha} c_{\eta}^{\alpha})_{,\tau} + \sum_{\alpha=1}^{nop} \left[-c_{\eta}^{\alpha} \frac{k_{ij}^{\alpha}}{\mu^{\alpha}} (P_j^{\alpha} + \rho^{\alpha} g z_{,j}) \right]_{,j} = \sum_{\alpha=1}^{nop} (\phi S^{\alpha} D_{ij}^{\alpha} c_{\eta,j}^{\alpha})_{,i} + Q_{\eta}$$

(5-58a & 5-58b)

$$\omega_{\eta}^{\alpha} = \frac{c_{\eta}^{\alpha}}{\sum_{\eta=1}^{nos} c_{\eta}^{\alpha}}$$

(5-59)

$$\sum_{\eta=1}^{nos} \omega_{\eta}^{\alpha} = 1$$

(5-60)

Instantaneous thermodynamic phase equilibrium equations:

$$\left.\begin{aligned} F_i^{o}(\omega_\eta^{o},P^{o}) &= F_i^{w}(\omega_\eta^{w},P^{w}) \\ F_i^{w}(\omega_\eta^{w},P^{w}) &= F_{ig}(\omega_\eta^{g},P^{g}) \end{aligned}\right\} \quad i=1,2,...,nop, \quad 1\le\eta\le nop \tag{5-61}$$

Properties

If density and viscosity of the fluid is dependent on concentration in Equation 5-52 and Equation 5-53; then, modify the account for concentration:

$$\rho_s^{\alpha} = \rho_s^{\alpha}(\omega_\eta^{\alpha},P^{\alpha}) \tag{5-62}$$

and

$$\mu_s^{\alpha} = \mu_s^{\alpha}(\omega_\eta^{\alpha},P^{\alpha}) \tag{6-63}$$

Boundary Conditions

Admissible boundary conditions for mass conservation equation:

$$C_\eta^{\alpha} = C_\eta^{\alpha}(x_1,x_2,x_3,\tau,V,...)$$

$$-\phi S^{\alpha} D_{ij}^{\alpha} c_{\eta,j}^{\alpha} = q_\eta^{\alpha} \tag{5-64}$$

Table 5-5 is a list of variables for multi-phase fluid flow.

Table 5-5: List of Variables

Symbol	Equation	Number of Equations	Equation Type
P^{α}	(5-8.3)	nop	differential
ρ^{α}	(5-8.4)	nop	algebraic
P_c^{α}	(5-8.6)	nop-1	algebraic
S^{α}	(5-8.5)	nop-1	algebraic
S^{α}	(5-8.7)	1	algebraic
c_{η}^{α}	(5-8.10)	nos	differential
c_{η}^{α}	(5-8.11)	nop	algebraic
c_{η}^{α}	(5-8.13)	nop*nos-nop-nos	algebraic
ρ_s^{α}	(5-8.14)	nop	algebraic
μ_s^{α}	(5-8.15)	nop	algebraic

Confined Aquifer

Governing Equations

Compressible and incompressible flow in confined aquifers is defined with this equation:

$$s_s P_{,\tau} = \left[K(P_{,j} + \rho g z_{,j})\right]_{,j} + \rho g q \qquad (5\text{-}65)$$

Equation 5-70 for (h-z) < 2000 m and for incompressible flow:

$$s_s h_{,\tau} = (K\, h_{,j})_{,j} + q \tag{5-66}$$

Properties

For compressible flow the fluid density (ρ) is defined in terms of isothermal liquid compressibility (β_L):

$$\rho = \rho_o e^{\beta_L (P - P_o)} \tag{5-67}$$

Specific storage (s_s):

$$s_s = \rho \phi g \left(\beta_L - \beta_s + \frac{\alpha}{\phi} \right) \tag{5-68}$$

Boundary Conditions

These are boundary conditions for a confined aquifer:

In terms of hydraulic head:

$$h = h(x_1, x_2, x_3, \tau, V, \ldots)$$

$$-K\, h_j = q''$$

(5-69)

In terms of pressure:

$$P = \rho g(h - z) = P(x_1, x_2, x_3, \tau, V, \ldots)$$

$$-K(P_j + \rho g z_j) = \rho g q''$$

(5-70)

Unconfined Aquifer

Governing Equation

This is the governing equation for an unconfined aquifer:

$$\phi_d h_{,\tau} = (K\ h\ h_{,j})_{,j} + Q \tag{5-71}$$

Boundary Conditions

These are the boundary conditions for an unconfined aquifer:

$$h = h(x_1, x_2, x_3, \tau, V, \ldots)$$
$$-K\ h_{,j} = q'' \tag{5-72}$$

For free surface satisfy these conditions simultaneously:

$$-K\ h_{,j} = q'' \quad \text{and} \quad h = z \tag{5-73}$$

Table 5-6 identifies simulation types and corresponding equations for multi-phase fluid flow.

Table 5-6: Simulation Types and Corresponding Equations

Type	Options	Equations
Phase	{Single ¦ Multiple}	{5-52 ¦ 5-52, 5-54,5-56}
Flow Type	{Incompressible ¦ Compressible}	{* ¦ 5-53}
Matrix Type	{Incompressible ¦ Compressible}	{* ¦ 5-57}
Species	{Single ¦ Multiple}	{5-58, 5-62, 5-63 ¦ 5-58, 5-63}
* No equation is necessary for single phase unconfined aquifer in Equation 21 and for single phase confined aquifer in Equation 17 or Equation 18. Set incompressible solid grains α_s to zero.		

5.9 STRESS EQUATIONS

Governing Equations:

In x-direction:

$$D_{11}\frac{\partial^2 u}{\partial x^2} + D_{44}\frac{\partial^2 u}{\partial y^2} + D_{66}\frac{\partial^2 u}{\partial z^2} + D_{12}\frac{\partial^2 v}{\partial x \partial y} + D_{44}\frac{\partial^2 v}{\partial y \partial x} + D_{13}\frac{\partial^2 w}{\partial x \partial z} + D_{66}\frac{\partial^2 w}{\partial z \partial x} = \frac{\partial}{\partial x}\left[(D_{11}+D_{12}+D_{13})\ (\alpha_T \Delta T + \alpha_M \Delta M)\right] - \left[\frac{\partial \sigma^\circ_{xx}}{\partial x} + \frac{\partial \sigma^\circ_{xy}}{\partial y} + \frac{\partial \sigma^\circ_{zx}}{\partial z}\right] + b_x \quad \textbf{(7-12)}$$

In y-direction:

$$D_{44}\frac{\partial^2 u}{\partial x \partial y} + D_{21}\frac{\partial^2 u}{\partial y \partial x} + D_{44}\frac{\partial^2 v}{\partial x^2} + D_{22}\frac{\partial^2 v}{\partial y^2} + D_{55}\frac{\partial^2 v}{\partial z^2} + D_{23}\frac{\partial^2 w}{\partial y \partial z} + D_{55}\frac{\partial^2 w}{\partial z \partial y} = \frac{\partial}{\partial y}\left[(D_{21}+D_{22}+D_{23})\ (\alpha_T \Delta T + \alpha_M \Delta M)\right] - \left[\frac{\partial \sigma^\circ_{xy}}{\partial x} + \frac{\partial \sigma^\circ_{yy}}{\partial y} + \frac{\partial \sigma^\circ_{yz}}{\partial z}\right] + b_y \quad \textbf{(7-13)}$$

In z-direction:

$$D_{66}\frac{\partial^2 u}{\partial x \partial z} + D_{31}\frac{\partial^2 u}{\partial z \partial x} + D_{55}\frac{\partial^2 v}{\partial y \partial z} + D_{32}\frac{\partial^2 v}{\partial z \partial y} + D_{66}\frac{\partial^2 w}{\partial x^2} + D_{55}\frac{\partial^2 w}{\partial y^2} + D_{33}\frac{\partial^2 w}{\partial z^2} = \frac{\partial}{\partial z}\left[(D_{31}+D_{32}+D_{33})\ (\alpha_T \Delta T + \alpha_M \Delta M)\right] - \left[\frac{\partial \sigma^o_{zx}}{\partial x} + \frac{\partial \sigma^o_{yz}}{\partial y} + \frac{\partial \sigma^o_{zz}}{\partial z}\right] + b_z \quad \textbf{(7-14)}$$

Properties:

Isotropic plane stress:

$$D = \frac{E}{1-\mu^2}\begin{bmatrix} 1 & \mu & 0 \\ \mu & 1 & 0 \\ 0 & 0 & \frac{1-\mu}{2} \end{bmatrix} \quad \textbf{(7-15)}$$

Isotropic plane strain:

$$D = \frac{E}{(1-\mu^2)\ (1-2\mu)}\begin{bmatrix} 1-\mu & \mu & 0 \\ \mu & 1-\mu & 0 \\ 0 & 0 & \frac{1-2\mu}{2} \end{bmatrix} \quad \textbf{(7-16)}$$

Isotropic 3-D:

$$D = \frac{E}{(1-\mu^2)\,(1-2\mu)} \begin{bmatrix} 1-\mu & \mu & \mu & 0 & 0 & 0 \\ \mu & 1-\mu & \mu & 0 & 0 & 0 \\ \mu & \mu & 1-\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\mu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\mu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\mu}{2} \end{bmatrix} \quad \text{(7-17)}$$

5.9 MULTI-PHASE RADON TRANSPORT IN POROUS MEDIA

Governing Equations

These are equations for fluid flow in primitive variables.

Conservation of mass

$$u_{j,j} = 0 \quad \text{in } \Omega_G \tag{7-18}$$

Conservation of momentum

$$\rho \left[\frac{\partial u_i}{\partial \tau} + u_j\, u_{i,j} \right] = -p_{,i} + \rho g_i \left[1 - \beta_T (T - T_o) - \beta_M (\rho_v - \rho_{v,o}) - \beta_C (C - C_o) \right] + \mu_e \left[u_{i,j} + u_{j,i} \right]_{,j} + \frac{2}{3} \rho \kappa_{,i} \quad \text{in } \Omega_G \tag{7-19}$$

Use the Penalty Finite Element Method (PFEM) to solve the fluid flow equations in primitive variables, Equation 5-1 is replaced by this equation:

$$\bar{\epsilon}\,(u_{j,j}) = -p \quad \text{in } \Omega_G \tag{7-20}$$

In Equation 5-3, ϵ^- denotes the penalty parameter. (See Subsection 2.1, Line 11) Equation 5-3 eliminates the pressure term to obtain the solution of Equation 5-2. If Library Equations 1, 2, and 3 are solved, only the velocity field will be obtained. Solve Library Equation 8 to obtain the pressure distribution.

Properties

$$\mu_e = \begin{cases} \mu \text{ in } \Omega_G \text{ for laminar flow} \\ \mu+\mu_T \text{ in } \Omega_G \text{ for turbulent flow} \end{cases} \tag{7-21}$$

For turbulent flow simulations the dynamic viscosity, μ, is replaced by $\mu+\mu_T$. Set the laminar flow simulations $2/3\rho\kappa_{,i}$ to zero.

Boundary Conditions

These are boundary conditions for fluid flow equations in primitive variables:

$$u_i = u_i(x_1,x_2,x_3,\tau,V,\ldots) \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{s\text{-}G}$$

$$u_{,i}\cdot n = 0 \quad \text{on } \Gamma_i \text{ or } \Gamma_o \text{ or } \Gamma_{s\text{-}G} \tag{7-22}$$

NOMENCLATURE

A_T Isothermal moisture capacity based on water vapor density [m^3/kg]

B_ρ Thermo-gradient coefficient based on water vapor density [kg/kg.K]

C Contaminant concentration [kg/m^3]

C_M Isothermal moisture capacity used in Luikov's theory [kg/kg.°M]

C_o Reference contaminant concentration used in buoyancy calculation [kg/m^3]

C_p Specific heat [J/kg.K]

c_η^α Concentration of species η in phase α [kg/m^3]

D_a Molecular diffusivity of water vapor in air [m^2/s]

D_c Molecular diffusivity of contaminant in air [m^2/s]

D_v Water vapor diffusivity [m^2/s]

D_{ij}^α Diffusivity tensor of phase α [m^2/s]

F_{ij} Script-F factor [dimensionless]

Fs Thermal radiation view factor [dimensionless]

g Gravitational acceleration [m/s^2]

h Head ($P/\rho g+z$) [m]

h_M Convective mass transfer coefficient [m/s]

$h_{M,M}$ Convective mass transfer coefficient used in Luikov's theory [$kg/m^2.s.°M$]

h_T Convective heat transfer coefficient [$W/m^2.K$]

k	Thermal conductivity [W/m.K]
k_M	Moisture conductivity used in Luikov's theory [kg/m.s.°M]
K^{α}_{ij}	$k^{\alpha}_{ij}\rho^{\alpha}g/\mu^{\alpha}$ [m/s]
k^{α}_{ij}	Intrinsic permeability of the material for phase α [m^2]
M	Mass transfer potential [°M]
m^{α}	Molar mass of the gas [?]
n	Normal vector [m]
nop	Number of phases [dimensionless]
nos	Number of species [dimensionless]
P	Total pressure [$kg/m.s^2$]
p	Pressure [$kg/m.s^2$]
P^{α}	Pressure for phase α [$kg/m.s^2$]
P^{α}_{c}	Capillary pressure at the interface of phases [$kg/m.s^2$]
P^{α}_{o}	Reference fluid pressure for phase α [$kg/m.s^2$]
Q	q dz [m/s]
q	Volumetric flow rate of fluid per unit volume of rock [1/s]
q''	Boundary flux for hydraulic head equation [m/s]
Q_C	Internal contaminant source/sink [kg/m^3]
Q_M	Internal moisture source/sink [kg/m^3]
Q_T	Internal heat source/sink [W/m^3]
q''_C	Imposed contaminant flux [$kg/m^2.s$]
q''_M	Imposed mass flux [$kg/m^2.s$]

q''_T Imposed heat flux [W/m^2]

q^{α}_{η} Boundary mass flux of contaminant η in phase α [$kg/m^2.s$]

Q^{α} Sink/source for phase α [$kg/m^3.s$]

q^{α} Boundary flux of phase α [m/s]

Q_{η} Sink/source for specie η [$kg/m^3.s$]

R Perfect gas constant [461.52 J/kg.K]

s_s Specific storage [1/m]

S^{α} Volumetric saturation for phase α (V^{α}/V_p) [dimensionless]

T Temperature [K]

T_o Reference temperature used in buoyancy calculation [K]

T_s Radiation sink/source temperature [K]

T^{α} Temperature for phase α [K]

u Velocity [m/s] or displacement [m]

U_e Equilibrium moisture content [kg/kg]

Uo Reference velocity [m/s]

U^{α} Darcy's velocity for phase α ($\phi S^{\alpha} u^{\alpha}$) [m/s]

V_P Volume of pore [m^3]

V_T Total volume [m^3]

V^{α} Volume of phase α ($V_T \phi S^{\alpha}$) [m^3]

x Cartesian coordinate direction [m]

z Height above the datum [m]

Z^{α} Compressibility factor for gaseous phase α [dimensionless]

GREEK LETTERS

α Compressibility of porous matrix [m.s^2/kg]

α_s Compressibility of solid grains [m.s^2/kg]

β_C Contaminant expansion coefficient [m^3/kg]

β_L^α Isothermal liquid compressibility [m.s^2/kg]

β_M Moisture expansion coefficient [m^3/kg]

β_S Isothermal solid grain compressibility [m.s^2/kg]

β_T Thermal expansion coefficient [1/K]

Γ Surface [dimensionless]

γ Vapor diffusivity/total mass diffusivity [dimensionless]

Δn Distance from wall [m]

δ Thermo-gradient coefficient [1/K]

ϵ Emissivity [dimensionless] or turbulent dissipation rate [m^2/s^3]

ϵ^- Penalty parameter [dimensionless]

η Index for the species [dimensionless]

κ Turbulent kinetic energy [m^2/s^2]

Λ Porosity [dimensionless]

λ Heat of sorption [J/kg]

μ Dynamic viscosity [kg/m.s]

μ_T Turbulent eddy viscosity [kg/m.s]

μ^α Viscosity of pure fluid in phase α [kg/m.s]

ρ Density [kg/m^3]

ρ_b Bulk density [kg/m^3]

ρ_v Water vapor density [kg/m^3]

$\rho_{v,o}$ Reference water vapor density used in buoyancy calculation [kg/m^3]

ρ^α Density of pure fluid in phase α [kg/m^3]

ρ_o^α Reference pure fluid density in phase α [kg/m^3]

σ Stefan-Boltzmann constant [W/m^2.K^4]

σ_C Empirical constant used in the κ-ϵ turbulence model [dimensionless]

σ_M Empirical constant used in the κ-ϵ turbulence model [dimensionless]

σ_T Empirical constant used in the κ-ϵ turbulence model [dimensionless]

σ_ϵ Empirical constant used in the κ-ϵ turbulence model [dimensionless]

σ_κ Empirical constant used in the κ-ϵ turbulence model [dimensionless]

τ Time [s]

τ_o Tortuosity [dimensionless]

Φ Dissipation function [1/s^2]

ϕ Relative humidity [dimensionless and $0 \leq \phi \leq 1$]

ϕ Porosity (V_p/V_T) [dimensionless]

ϕ_d Drainage porosity (part of porosity drained by gravity) [dimensionless]

ψ Stream function [m^2/s]

Ω Domain [dimensionless]

$\mathfrak{w}$ Vorticity [1/s]

ω_η^α Mass fraction of species η in phase α ($c_\eta^\alpha/\Sigma c_\eta^\alpha$)

SUBSCRIPTS AND SUPERSCRIPTS

e	Effective
G	Gas
i	Inflow
n	Wall node
n+1	Node away from wall
o	Outflow
R	Lump
S	Solid
v	Vapor
α	Ambient
*	Surface

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SECTION 6

EXAMPLE SIMULATIONS

INTRODUCTION

This section provides some example simulations participating to building science. A brief physical description of each example is followed by the input deck and corresponding results. The data files provided in this Section familiarize the user with the general format of an input deck. In the presentation of the results several post-processors are used. These post-processors are not included in the software package. However, the formats used to create the output files that are used by the post-processors are provided in Appendix A. Therefore, the user may utilize an existing or a commercially available graphics package to perform the necessary plots.

6.1 NATURAL CONVECTION IN A SQUARE CAVITY USING (ω-ψ)

In this example, natural convection in a square cavity is simulated. In the simulations the vorticity and stream function formulations are used. The right-hand and left-hand side wall temperatures are prescribed to 310 K and 300 K, respectively. Along the boundaries the value of the stream function is set to zero. The wall vorticities are calculated using wall vorticity equation number 1 (NVORTY = 1). In the simulations, 784 (28x28) nodes and 729 four-node linear rectangular elements are used. In the mesh generation the spacing factor is set 1 (SP = 1), therefore the mesh is not graded. In the simulation the relaxation parameters are set to 0.3, 0.4 and 0.5 for the stream function, vorticity and energy equations, respectively. For all of the equations the error tolerance is set to 0.1%. The output options 21, 22 and 23 are invoked to create <FL>.FLX, <FL>.MSH and <FL>.RES files that are used by the post-processor to plot contours and vectors.

Two different simulations corresponding to Raleigh numbers of 10^3 and 10^4 are performed. In the simulations the Rayleigh numbers are changed by increasing the size of the cavity (SCALE = 0.01053 and 0.0227 for Ra = 10^3 and 10^4, respectively). The results of these simulations are shown in Figure 6-1.1 and 6-1.2. The temperature isotherms, velocity vectors, stream function and vorticity contours are shown in these figures. By post-processing the stream functions, the velocities are calculated at the element centroids.

```
EXAMPLE 1: NATURAL CONVECTION IN A SQUARE CAVITY (VORTICITY STREAM).
     784   729     1     0     3     5
       0     0     0     0     0
       1     0    50
 0.01053     0     2     1
       0     0
       5     4     5     6     7    11
       4   0.0   0.3   0.1   0.0
       5   0.0   0.4   0.1   0.0
       6   0.0   1.0   0.1   0.0
       7   0.0   1.0   0.1   0.0
      11 305.0   0.5   0.1   0.0
       0 -9.81     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       0     0     0     0     0     0     0     0     0     0
       9     3    21    22    23    25    50   504   505   511
       0
```

```
SECTION   II: NODE GENERATION
       1     1    28   1.0    0.0    0.0   0.0   0.0    1.0   0.0
     757     1   784   1.0    1.0    0.0   0.0   1.0    1.0   0.0
       1    28   757   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       2    28   758   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       3    28   759   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       4    28   760   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       5    28   761   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       6    28   762   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       7    28   763   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       8    28   764   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       9    28   765   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      10    28   766   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      11    28   767   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      12    28   768   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      13    28   769   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      14    28   770   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      15    28   771   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      16    28   772   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      17    28   773   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      18    28   774   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      19    28   775   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      20    28   776   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      21    28   777   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      22    28   778   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      23    28   779   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      24    28   780   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      25    28   781   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      26    28   782   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      27    28   783   1.0    0.0 -32767   0.0   1.0 -32767   0.0
      28    28   784   1.0    0.0 -32767   0.0   1.0 -32767   0.0
       0     0     0   0.0    0.0    0.0   0.0   0.0    0.0   0.0
```

```
SECTION  III:  ELEMENT GENERATION
      1     27    703      1    1.0     28     29     30      2      1
      2     27    704      1    1.0     28     30     31      3      2
      3     27    705      1    1.0     28     31     32      4      3
      4     27    706      1    1.0     28     32     33      5      4
      5     27    707      1    1.0     28     33     34      6      5
      6     27    708      1    1.0     28     34     35      7      6
      7     27    709      1    1.0     28     35     36      8      7
      8     27    710      1    1.0     28     36     37      9      8
      9     27    711      1    1.0     28     37     38     10      9
     10     27    712      1    1.0     28     38     39     11     10
     11     27    713      1    1.0     28     39     40     12     11
     12     27    714      1    1.0     28     40     41     13     12
     13     27    715      1    1.0     28     41     42     14     13
     14     27    716      1    1.0     28     42     43     15     14
     15     27    717      1    1.0     28     43     44     16     15
     16     27    718      1    1.0     28     44     45     17     16
     17     27    719      1    1.0     28     45     46     18     17
     18     27    720      1    1.0     28     46     47     19     18
     19     27    721      1    1.0     28     47     48     20     19
     20     27    722      1    1.0     28     48     49     21     20
     21     27    723      1    1.0     28     49     50     22     21
     22     27    724      1    1.0     28     50     51     23     22
     23     27    725      1    1.0     28     51     52     24     23
     24     27    726      1    1.0     28     52     53     25     24
     25     27    727      1    1.0     28     53     54     26     25
     26     27    728      1    1.0     28     54     55     27     26
     27     27    729      1    1.0     28     55     56     28     27
      0      0      0      0    0.0      0      0      0      0      0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
AIR
 0.0267  1.145  1.145    1007      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
1.87E-5      0      0  0.0033      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
      0
    300
    310
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
  1   1   28     1    -1     1    1    2
 29  28  729     1    -1     1    1    0
 56  28  756     1    -1     1    1    0
757   1  784     1    -1     1    1    3
  0   0    0     0     0     0    0    0
SECTION VIII:  WALL VORTICITY DISTANCE SPECIFICATION
  1   1   28  0.037035
 29  28  729  0.037035
 56  28  756  0.037035
757   1  784  0.037035
  0   0    0  0.000000
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
      0    0     0     0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

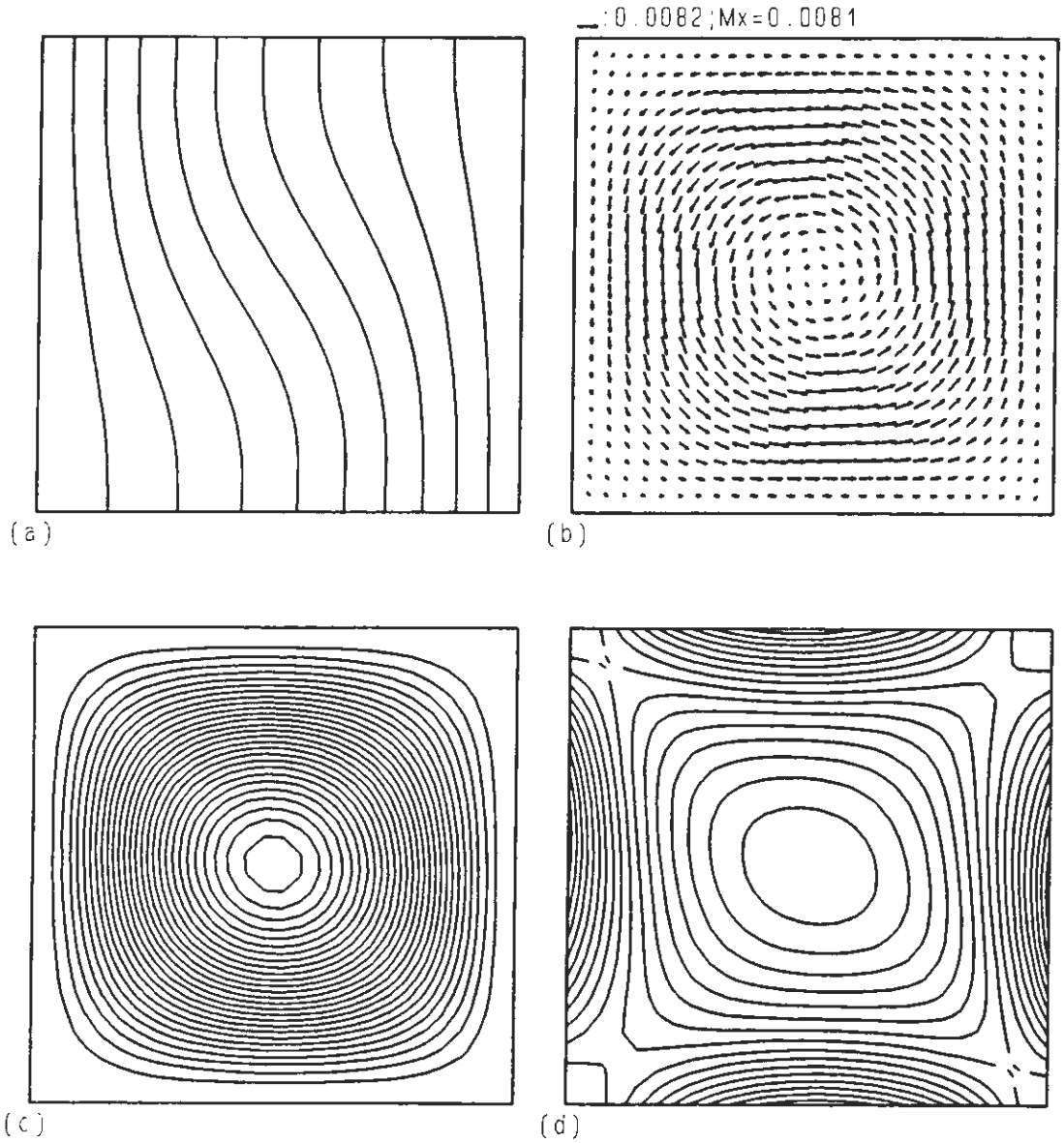


Figure 6-1.1 Natural convection in a square cavity results for $Ra=10^3$ using vorticity stream function: (a) isotherm, (b) velocity vector, (c) stream function and (d) vorticity distributions.

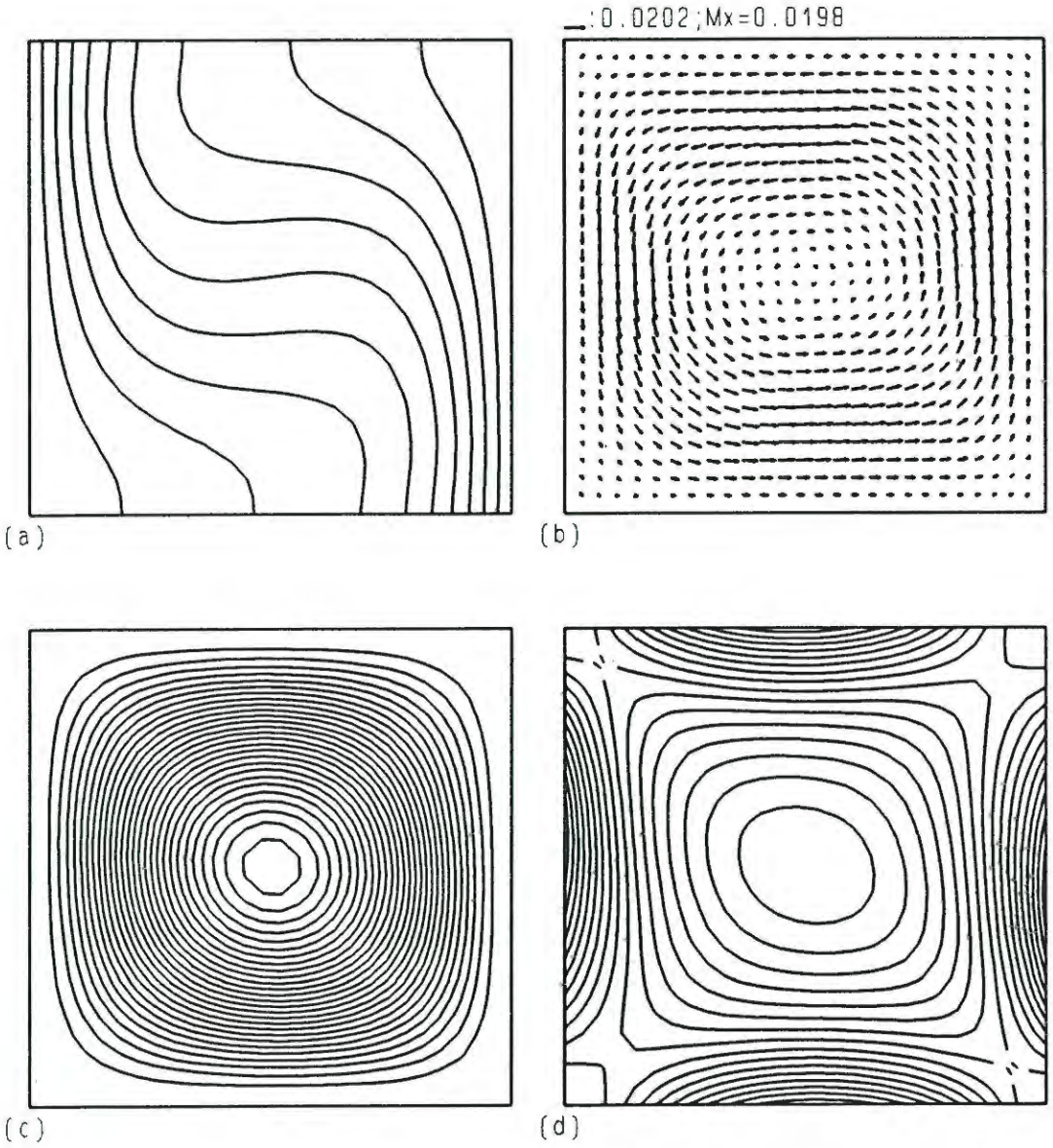


Figure 6-1.2 Natural convection in a square cavity results for $Ra=10^4$ using vorticity stream function: (a) isotherm, (b) velocity vector, (c) stream function and (d) vorticity distributions.

6.2 NATURAL CONVECTION IN A SQUARE CAVITY USING PFEM

In this example the same problem defined in Subsection 6.1 is simulated using the Penalty Finite Element Method (PFEM) formulations. Along the boundaries the value of the velocity components are set to zero to represent the no-slip boundary condition. The penalty parameter is set to 10^5 [CON(26) = 10E5].

The simulation results are compared favorably with the results obtained from the previous example using the vorticity and velocity fields for Ra = 10^3 and Ra = 10^4 are shown in Figure 6-2.1 and 6-2.2, respectively. The velocities increases with the increase in the Raleigh number. Similar to the first example, different Raleigh numbers are simulated by modifying the size of the cavity (SCALE = 0.01053 and 0.0227 for Ra = 10^3 and 10^4, respectively).

Note that, in the PFEM the velocities are obtained at the nodes (primitive equations are solved) whereas in the stream function and vorticity formulations they are calculated at the element centroid. However, along with the vorticity and stream function equations if equations 6 and 7 are solved (Poisson's equations for u- and v-velocities) the velocities at the nodes can be obtained.

```
EXAMPLE 2: NATURAL CONVECTION IN A SQUARE CAVITY USING PENALTY FEM.
     784    729       1     0     3     5
       0      0       0     0     0
       3      0      50
 0.01053      0       2     1
       0      0
       3      1       2    10
       1    0.0     0.5   0.1   0.0
       2    0.0     0.5   0.1   0.0
      10  305.0     0.5   0.1   0.0
       0  -9.81       0   305     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0   1E5     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       0      0       0     0     0     0     0     0     0     0
       8     19      21    22    23    50   501   502   510
       0
```

```
SECTION    II: NODE GENERATION
       1      1      28      1.0     0.0     0.0     0.0     0.0     1.0     0.0
     757      1     784      1.0     1.0     0.0     0.0     1.0     1.0     0.0
       1     28     757      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       2     28     758      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       3     28     759      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       4     28     760      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       5     28     761      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       6     28     762      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       7     28     763      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       8     28     764      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       9     28     765      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      10     28     766      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      11     28     767      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      12     28     768      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      13     28     769      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      14     28     770      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      15     28     771      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      16     28     772      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      17     28     773      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      18     28     774      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      19     28     775      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      20     28     776      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      21     28     777      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      22     28     778      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      23     28     779      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      24     28     780      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      25     28     781      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      26     28     782      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      27     28     783      1.0     0.0  -32767     0.0     1.0  -32767     0.0
      28     28     784      1.0     0.0  -32767     0.0     1.0  -32767     0.0
       0      0       0      0.0     0.0     0.0     0.0     0.0     0.0     0.0
SECTION   III:  ELEMENT GENERATION
       1     27     703        1     1.0      28      29      30       2       1
```

```
      2     27    704      1    1.0     28     30     31      3      2
      3     27    705      1    1.0     28     31     32      4      3
      4     27    706      1    1.0     28     32     33      5      4
      5     27    707      1    1.0     28     33     34      6      5
      6     27    708      1    1.0     28     34     35      7      6
      7     27    709      1    1.0     28     35     36      8      7
      8     27    710      1    1.0     28     36     37      9      8
      9     27    711      1    1.0     28     37     38     10      9
     10     27    712      1    1.0     28     38     39     11     10
     11     27    713      1    1.0     28     39     40     12     11
     12     27    714      1    1.0     28     40     41     13     12
     13     27    715      1    1.0     28     41     42     14     13
     14     27    716      1    1.0     28     42     43     15     14
     15     27    717      1    1.0     28     43     44     16     15
     16     27    718      1    1.0     28     44     45     17     16
     17     27    719      1    1.0     28     45     46     18     17
     18     27    720      1    1.0     28     46     47     19     18
     19     27    721      1    1.0     28     47     48     20     19
     20     27    722      1    1.0     28     48     49     21     20
     21     27    723      1    1.0     28     49     50     22     21
     22     27    724      1    1.0     28     50     51     23     22
     23     27    725      1    1.0     28     51     52     24     23
     24     27    726      1    1.0     28     52     53     25     24
     25     27    727      1    1.0     28     53     54     26     25
     26     27    728      1    1.0     28     54     55     27     26
     27     27    729      1    1.0     28     55     56     28     27
      0      0      0      0    0.0      0      0      0      0      0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
AIR
 0.0267  1.145  1.145   1007      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
1.87E-5      0      0 0.0033      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
      0
    300
    310
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
  1   1   28     1     1     2
 29  28  729     1     1     0
 56  28  756     1     1     0
757   1  784     1     1     3
  0   0    0     0     0     0
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
      0     0     0     0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

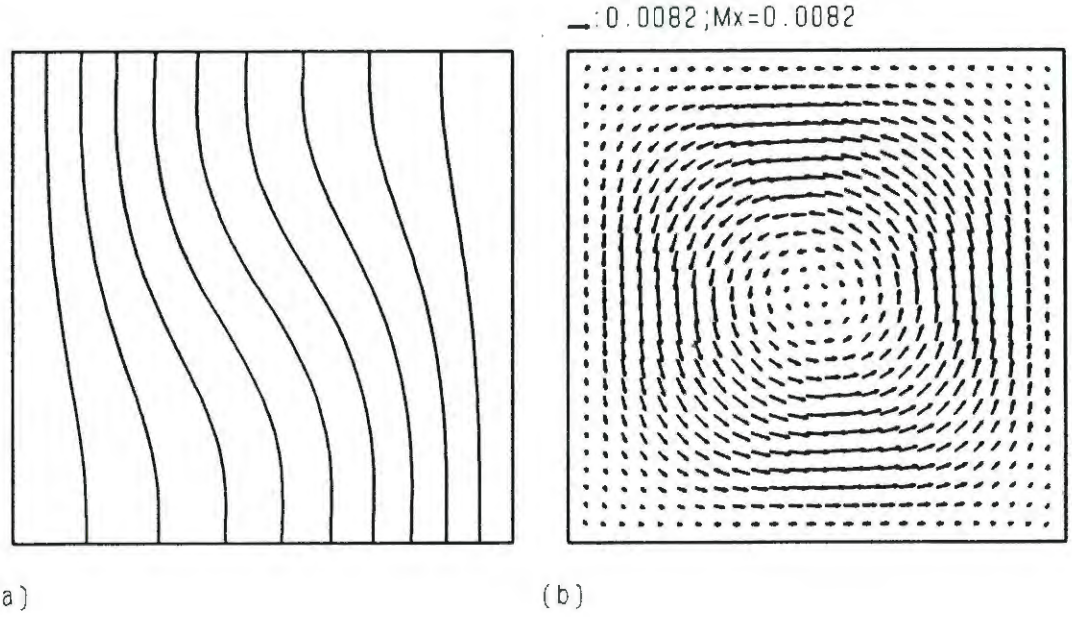


Figure 6-2.1 Natural convection in a square cavity results for $Ra=10^3$ using penalty finite element: (a) isotherm and (b) velocity vector distributions.

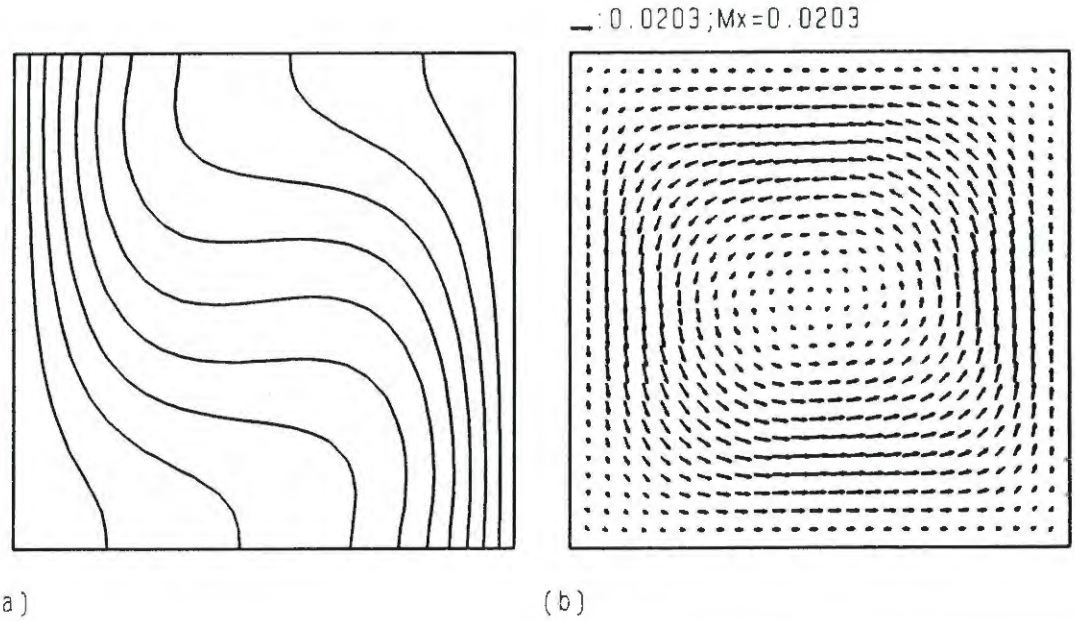


Figure 6-2.2 Natural convection in a square cavity results for $Ra=10^4$ using penalty finite element: (a) isotherm and (b) velocity distributions.

6.3 LAMINAR FLOW IN A DUCT SYSTEM

In this example laminar flow in a 0.5 m long duct system is simulated. In the simulations, 750 nodes and 686 four-node linear rectangular elements are used. Due to symmetry only half of the duct height is simulated. The upper part of the duct is made of 0.025 m thick brick. Therefore, the velocity components in the brick and brick-air interface are prescribed to 0. At the inlet the u- and v-velocity components are prescribed to be 0.0408 m/s, respectively. At the outlet natural boundary conditions are used. In the simulations the PFEM is used, the penalty parameter is set to 10^6 [CON(26) = 10E6].

Figure 6-3 shows the development of the velocity field. At the fully developed region the center line velocity is 0.0557 m/s which is very close to the theoretical value by Schlichting (1968).

```
EXAMPLE 3: LAMINAR FLOW IN A DUCT SYSTEM.
   750   686     2     0     2     5
     0     0     0     0     0
     2     0    50
     1     0     2     0
     0     0
     2     1     2
     1   0.0   0.5   0.1   0.0
     2   0.0   0.5   0.1   0.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0 1.0E6     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     8    19    21    22    23    50   501   502   510
     0
```

```
SECTION   II: NODE GENERATION
  1   15   736   1.0   0.0   0.000   0.0   0.5   0.000   0.0
  2   15   737   1.0   0.0   0.005   0.0   0.5   0.005   0.0
  3   15   738   1.0   0.0   0.010   0.0   0.5   0.010   0.0
  4   15   739   1.0   0.0   0.015   0.0   0.5   0.015   0.0
  5   15   740   1.0   0.0   0.020   0.0   0.5   0.020   0.0
  6   15   741   1.0   0.0   0.025   0.0   0.5   0.025   0.0
  7   15   742   1.0   0.0   0.030   0.0   0.5   0.030   0.0
  8   15   743   1.0   0.0   0.035   0.0   0.5   0.035   0.0
  9   15   744   1.0   0.0   0.040   0.0   0.5   0.040   0.0
 10   15   745   1.0   0.0   0.045   0.0   0.5   0.045   0.0
 11   15   746   1.0   0.0   0.050   0.0   0.5   0.050   0.0
 12   15   747   1.0   0.0   0.055   0.0   0.5   0.055   0.0
 13   15   748   1.0   0.0   0.060   0.0   0.5   0.060   0.0
 14   15   749   1.0   0.0   0.065   0.0   0.5   0.065   0.0
 15   15   750   1.0   0.0   0.070   0.0   0.5   0.070   0.0
  0    0     0     0     0       0     0     0       0     0
SECTION  III:  ELEMENT GENERATION
  1    1    49    1     1.0      15    16    17      02    01
 50    1    98    1     1.0      15    17    18      03    02
 99    1   147    1     1.0      15    18    19      04    03
148    1   196    1     1.0      15    19    20      05    04
197    1   245    1     1.0      15    20    21      06    05
246    1   294    1     1.0      15    21    22      07    06
295    1   343    1     1.0      15    22    23      08    07
344    1   392    1     1.0      15    23    24      09    08
393    1   441    1     1.0      15    24    25      10    09
442    1   490    2     1.0      15    25    26      11    10
491    1   539    2     1.0      15    26    27      12    11
540    1   588    2     1.0      15    27    28      13    12
589    1   637    2     1.0      15    28    29      14    13
638    1   686    2     1.0      15    29    30      15    14
  0    0     0    0       0       0     0     0       0     0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
AIR
```

```
  0.0267  1.145  1.145    1007     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
1.87E-5       0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
BRICK
     1.3   2050   2050     960     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
       0      0      0       0     0     0     0     0     0     0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
       0
  0.0408
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
   1   1   09      2     1
  16  15  736      D     1
  10  15  745      1     1
  11  15  746      1     1
  12  15  747      1     1
  13  15  748      1     1
  14  15  749      1     1
  15  15  750      1     1
   0   0    0      0     0
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
       0    0      0     0
SECTION    X:  POINT SOURCE SPECIFICATION
       0
```

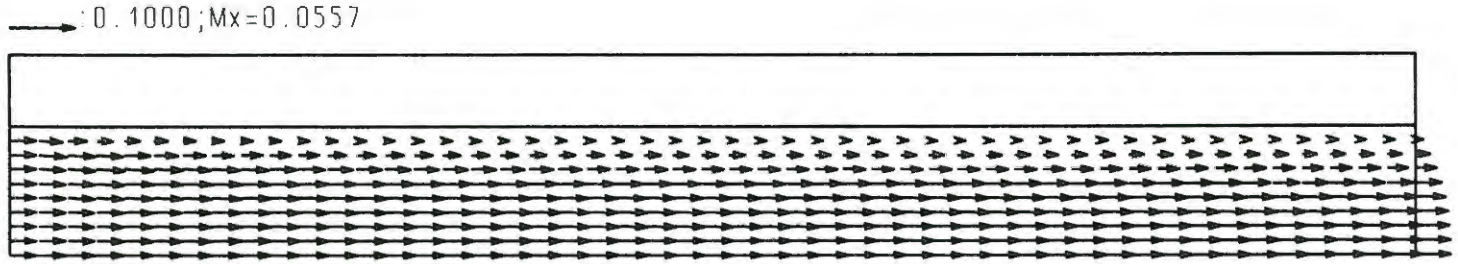


Figure 6-3 Velocity distribution in the upper half of the duct system.

6.4 THERMAL RADIATION IN A CAVITY

In this example, combined conduction and radiation effects on steady-state temperature distribution in cavity walls are simulated. The right-hand and left-hand side boundaries are prescribed to 300 K and 310 K, respectively. The cavity is treated as vacuum, therefore no conduction or convection is taking place within the cavity. In the simulations the emissivity of the material at the core of the cavity is varied. The mesh used in the simulations is shown in Figure 6-4.1.

Figure 6-4.2 and 6-4.3 show the effect of surface emissivity on steady-state temperature distributions for thermal conductivities of 0.267 and 0.0267 W/m.K, respectively. With increasing surface emissivity values the thermal gradients across the cavity decrease.

```
EXAMPLE 4: THERMAL RADIATION IN A CAVITY.
    880   800     1      0     2     5
      0     0     0      0     0
      1     0    50
    0.1     0     5      0
      0     0
      1    10
     10 325.0   0.2    0.1   0.0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
5.67E-8     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      0     0     0      0     0     0     0     0     0     0
      8    11    12     19    21    22    23    24    50   510
      0

VIWGET.VIW


SECTION   II:  NODE GENERATION
  1       31    311    1.0      0.0      0.0    0.0      2.0      0.0    0.0
342       22    518    1.0      2.6      0.0    0.0      7.4      0.0    0.0
540       31    850    1.0      8.0      0.0    0.0     10.0      0.0    0.0
352       22    528    1.0      2.6   3.3333    0.0      7.4   3.3333    0.0
353       22    529    1.0      2.6   6.6666    0.0      7.4   6.6666    0.0
 31       31    341    1.0      0.0     10.0    0.0      2.0     10.0    0.0
363       22    539    1.0      2.6     10.0    0.0      7.4     10.0    0.0
570       31    880    1.0      8.0     10.0    0.0     10.0     10.0    0.0
  1        1     31    1.0   -32767      0.0    0.0   -32767     10.0    0.0
 32        1     62    1.0   -32767      0.0    0.0   -32767     10.0    0.0
 63        1     93    1.0   -32767      0.0    0.0   -32767     10.0    0.0
 94        1    124    1.0   -32767      0.0    0.0   -32767     10.0    0.0
125        1    155    1.0   -32767      0.0    0.0   -32767     10.0    0.0
156        1    186    1.0   -32767      0.0    0.0   -32767     10.0    0.0
187        1    217    1.0   -32767      0.0    0.0   -32767     10.0    0.0
218        1    248    1.0   -32767      0.0    0.0   -32767     10.0    0.0
249        1    279    1.0   -32767      0.0    0.0   -32767     10.0    0.0
280        1    310    1.0   -32767      0.0    0.0   -32767     10.0    0.0
311        1    341    1.0   -32767      0.0    0.0   -32767     10.0    0.0
342        1    352    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
364        1    374    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
386        1    396    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
408        1    418    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
430        1    440    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
452        1    462    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
474        1    484    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
496        1    506    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
518        1    528    1.0   -32767      0.0    0.0   -32767   3.3333    0.0
353        1    363    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
375        1    385    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
397        1    407    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
419        1    429    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
441        1    451    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
463        1    473    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
485        1    495    1.0   -32767   6.6666    0.0   -32767     10.0    0.0
```

```
507       1    517    1.0   -32767   6.6666    0.0   -32767    10.0     0.0
529       1    539    1.0   -32767   6.6666    0.0   -32767    10.0     0.0
540       1    570    1.0   -32767      0.0    0.0   -32767    10.0     0.0
571       1    601    1.0   -32767      0.0    0.0   -32767    10.0     0.0
602       1    632    1.0   -32767      0.0    0.0   -32767    10.0     0.0
633       1    663    1.0   -32767      0.0    0.0   -32767    10.0     0.0
664       1    694    1.0   -32767      0.0    0.0   -32767    10.0     0.0
695       1    725    1.0   -32767      0.0    0.0   -32767    10.0     0.0
726       1    756    1.0   -32767      0.0    0.0   -32767    10.0     0.0
757       1    787    1.0   -32767      0.0    0.0   -32767    10.0     0.0
788       1    818    1.0   -32767      0.0    0.0   -32767    10.0     0.0
819       1    849    1.0   -32767      0.0    0.0   -32767    10.0     0.0
850       1    880    1.0   -32767      0.0    0.0   -32767    10.0     0.0
  0       0      0    0.0      0.0      0.0    0.0      0.0     0.0     0.0
SECTION   III:  ELEMENT GENERATION
      1       1     30       1     1.0       1     32     33      2       1
     31       1     60       1     1.0       1     63     64     33      32
     61       1     90       1     1.0       1     94     95     64      63
     91       1    120       1     1.0       1    125    126     95      94
    121       1    150       1     1.0       1    156    157    126     125
    151       1    180       1     1.0       1    187    188    157     156
    181       1    210       1     1.0       1    218    219    188     187
    211       1    240       1     1.0       1    249    250    219     218
    241       1    270       1     1.0       1    280    281    250     249
    271       1    300       1     1.0       1    311    312    281     280
    301       1    310       1     1.0       1    342    343    312     311
    311       1    320       1     1.0       1    364    365    343     342
    321       1    330       1     1.0       1    386    387    365     364
    331       1    340       1     1.0       1    408    409    387     386
    341       1    350       1     1.0       1    430    431    409     408
    351       1    360       1     1.0       1    452    453    431     430
    361       1    370       1     1.0       1    474    475    453     452
    371       1    380       1     1.0       1    496    497    475     474
    381       1    390       1     1.0       1    518    519    497     496
    391       1    400       1     1.0       1    540    541    519     518
    401       1    410       1     1.0       1    353    354    332     331
    411       1    420       1     1.0       1    375    376    354     353
    421       1    430       1     1.0       1    397    398    376     375
    431       1    440       1     1.0       1    419    420    398     397
    441       1    450       1     1.0       1    441    442    420     419
    451       1    460       1     1.0       1    463    464    442     441
    461       1    470       1     1.0       1    485    486    464     463
    471       1    480       1     1.0       1    507    508    486     485
    481       1    490       1     1.0       1    529    530    508     507
    491       1    500       1     1.0       1    560    561    530     529
    501       1    530       1     1.0       1    571    572    541     540
    531       1    560       1     1.0       1    602    603    572     571
    561       1    590       1     1.0       1    633    634    603     602
    591       1    620       1     1.0       1    664    665    634     633
    621       1    650       1     1.0       1    695    696    665     664
    651       1    680       1     1.0       1    726    727    696     695
    681       1    710       1     1.0       1    757    758    727     726
    711       1    740       1     1.0       1    788    789    758     757
    741       1    770       1     1.0       1    819    820    789     788
    771       1    800       1     1.0       1    850    851    820     819
      0       0      0       0     0.0       0      0      0      0       0
SECTION    IV:  MATERIAL PROPERTY SPECIFICATION
SOLID MATERIAL
  0.267   1.145   1.145     1007   0.33      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
      0       0       0        0      0      0      0      0      0       0
```

```
      0      0      0      0      0      0      0      0      0      0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
    300
    350
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
  1   1   31     1
850   1  880     2
  0   0    0     0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

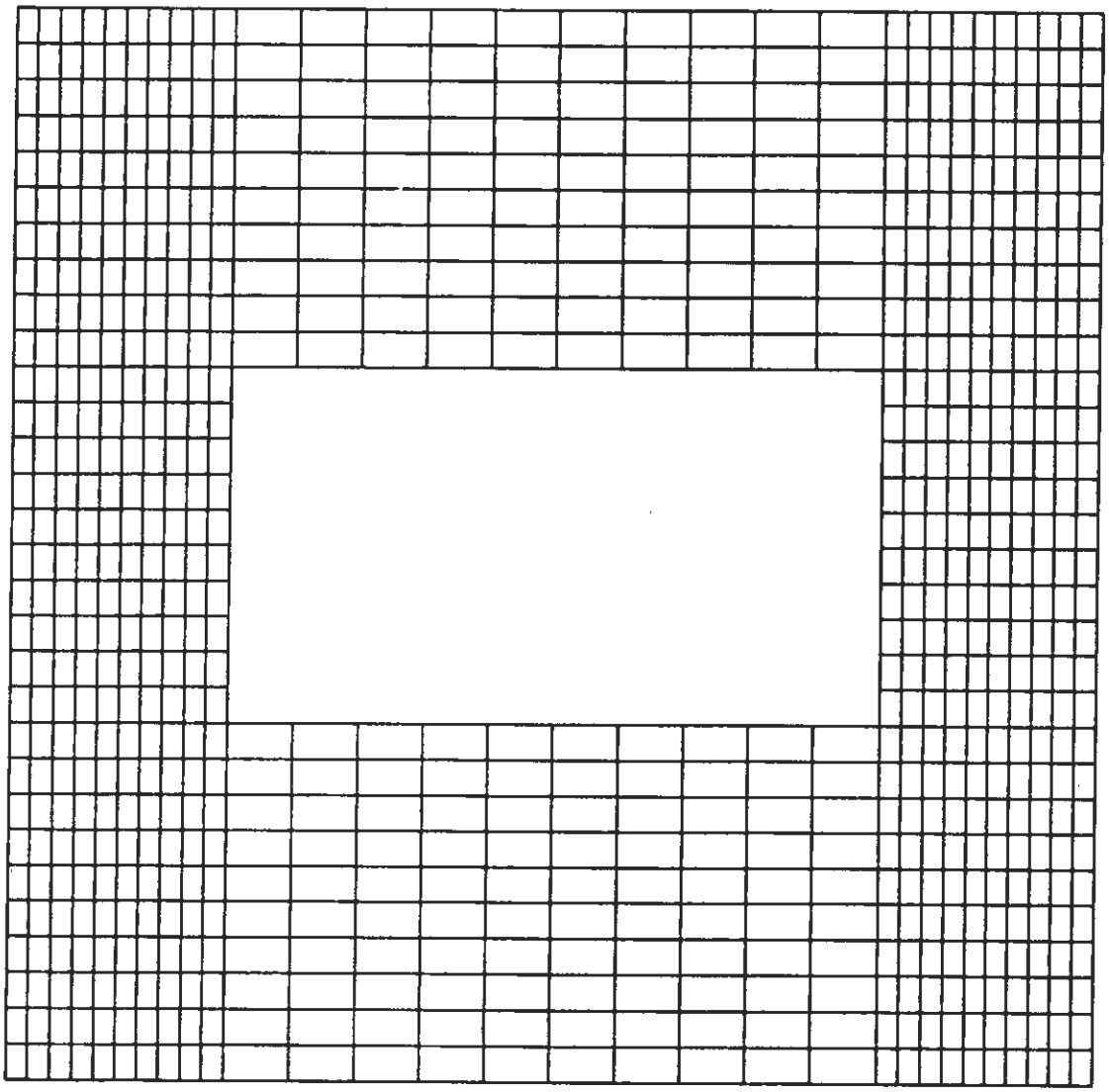


Figure 6-4.1 Mesh used in the cavity radiation problem.

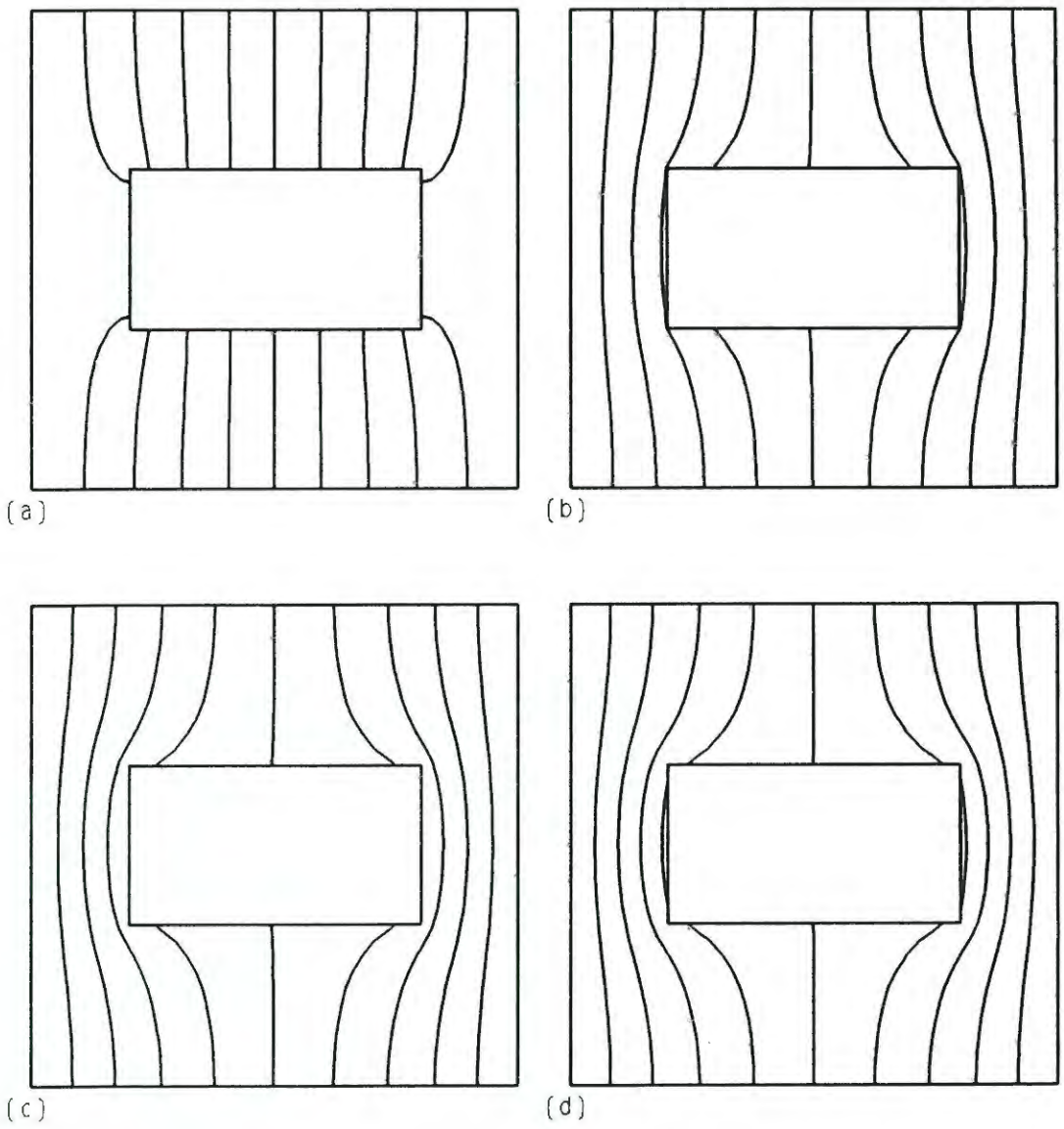


Figure 6-4.2 Normalized temperature distribution in a cavity walls with k=0.267 W/m.K for surface emittance of: (a) $\epsilon=0$, (b) $\epsilon=0.33$, (c) $\epsilon=0.66$ and (d) $\epsilon=1.0$.

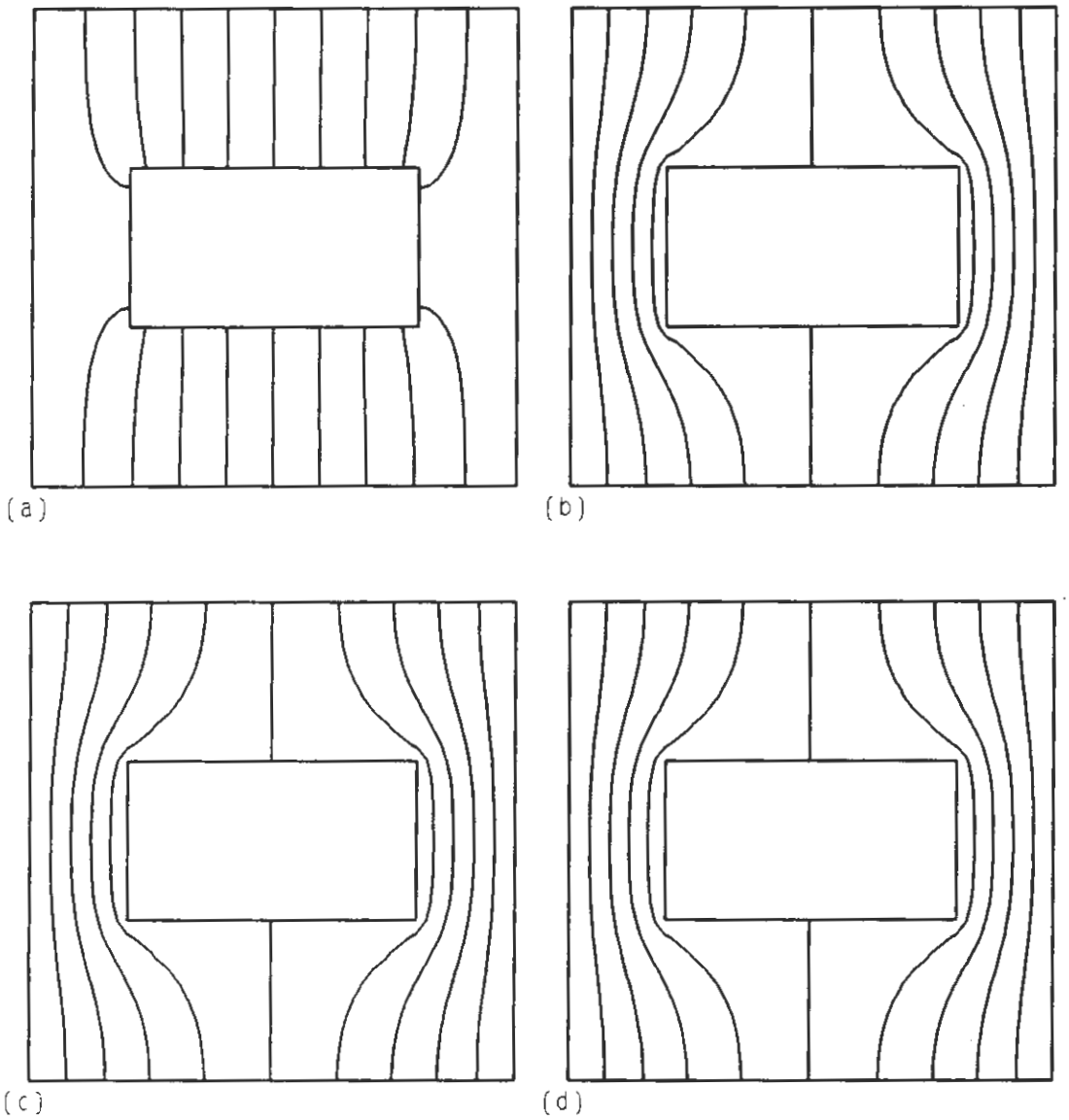


Figure 6-4.3 Normalized temperature distribution in cavity walls with k=0.0267 W/m.K for surface emittances of: (a) ϵ=0, (b) ϵ=0.33, (c) ϵ=0.66 and (d) ϵ=1.0.

6.5 FORMALDEHYDE EMISSION RATE OF A PARTICLE BOARD

In this example, formaldehyde emission rate from a particle board is simulated. In the simulations 4 one-dimensional quartic line elements are used (overall 17 nodes). The particle board is assumed to be an infinite slab (in y and z directions). One end (x=0) is impermeable and insulated whereas the other end (x=L) is exposed to cyclic convective boundary conditions. The cyclic variation of the air temperature and vapor concentration are simulated through user defined routine. In the boundary condition set value specifications, -1005 and -1006 are used to indicate that the ambient air temperature and vapor density are defined by the user. Subroutine VRPROP is modified to simulate these cyclic variations.

The convective air side temperature and relative humidity (the relative humidity is calculated from the water vapor density as a post processing) used in the simulation are shown in Figure 6-5 (a). The water vapor density and temperature histories at selective points (x=0, L/2 and L) are shown in Figure 6-5 (b) and 6-5 (c), respectively. The formaldehyde emission rate is calculated using the surface temperature and relative humidity variations as shown in Figure 6-5 (d). The equation and the constants used to calculate the formaldehyde emission rate are taken from Matthews at al. (1884 a and b).

```
EXAMPLE 5. FORMALDEHYDE EMISSION RATE OF A PARTICLE BOARD.
    17     4     1     1     0     4
     1     0     0   1.0   168
     2     0    50
   1.0     0     4     0
     0     0
     2    10    13
    10   300   1.0   0.0   1.0
    13 0.012   1.0   0.0   1.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     1
   300    10 0.015 0.004     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     6    21    22    23    50   510   513
     1
     0     1   168
```

```
SECTION   II: NODE GENERATION
     1      1     17    1.0     0.0     0.0     0.0  0.025    0.0    0.0
     0      0      0    0.0     0.0     0.0     0.0    0.0    0.0    0.0
SECTION  III:  ELEMENT GENERATION
     1      1      4     1   1.0      4      1      5      2      3      4
     0      0      0     0   0.0      0      0      0      0      0      0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
PARTICLE BOARD
 0.141    560    560    1630      0      0      0      0      0      0
2.1E-6   13.5    0.7   1.555  .0012 .06477 .51653 .11844 8.4725 2.5E+6
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
     0      0      0       0      0      0      0      0      0      0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
BC-1 INSIDE
   1.0  -1011    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 0.001  -1012    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
    17      0     17     -1     -1
     0      0      0      0      0
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
     0      0      0      0
SECTION    X:  POINT SOURCE SPECIFICATION
     0
```

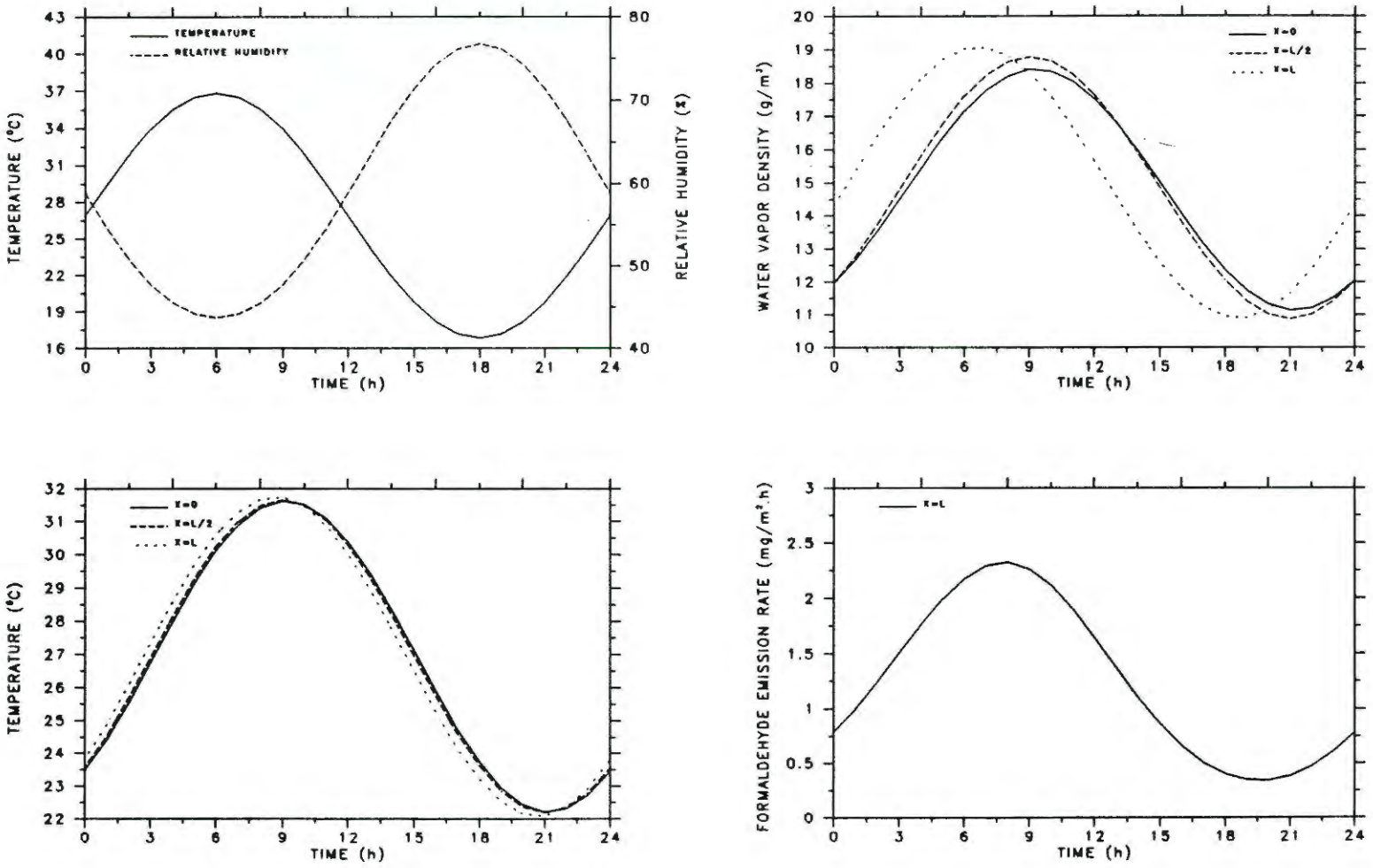


Figure 6-5 Formaldehyde emission rate of a particle board: (a) forcing functions, (b) vapor density distribution, (c) temperature distribution and (d) formaldehyde emission rate.

6.6 VELOCITY DISTRIBUTION IN A VENTILATED ROOM

In this example, various forced ventilation inlet and outlet configurations are studied. The room is discretized using 729 four-node rectangular elements (overall 784 nodes). The PFEM is used to solve the momentum equations in primitive variables. The penalty parameter is set to 10^6 [CON(26) = 10E6]. In the simulations only one inlet is modelled. At the inlet the velocity components are prescribed.

Figure 6-6 shows the effect of the outlet locations and arrangements on the velocity distribution. Each figure corresponds to a different arrangement of the outlets. These simulations are accomplished by modifying the boundary condition flags. At the outlets only natural boundary conditions are used. The input for boundary condition flag generation corresponding to each case is given below:

Case (a)	Case (b)	Case (c)	Case (b)
1 1 28 1 1	1 1 28 1 1	1 1 28 1 1	1 1 28 1 1
29 56 729 1 1	29 56 729 1 1	29 56 729 1 1	29 56 729 1 1
56 28 756 1 1	56 28 756 1 1	56 28 756 1 1	56 28 756 1 1
757 1 784 1 1	757 1 784 1 1	757 1 784 1 1	757 1 784 1 1
12 1 17 2 1	12 1 17 2 1	12 1 17 2 1	12 1 17 2 1
768 1 773 0 0	768 1 773 1 1	768 1 773 1 1	768 1 773 1 1
759 1 764 1 1	759 1 764 0 0	759 1 764 1 1	759 1 764 1 1
777 1 782 1 1	777 1 782 0 0	777 1 782 1 1	777 1 782 1 1
420 28 560 1 1	420 28 560 1 1	420 28 560 0 0	420 28 560 0 0
393 28 533 1 1	393 28 533 1 1	393 28 533 1 1	393 28 533 0 0
0 0 0 0 0	0 0 0 0 0	0 0 0 0 0	0 0 0 0 0

```
EXAMPLE 6: VELOCITY DISTRIBUTION IN A VENTILATED ROOM.
   784   729     1     0     2     5
     0     0     0     0     0
     2     0    50
   1.0     0     2     1
     0     0
     2     1     2
     1   0.0   0.5   0.1   0.0
     2   0.0   0.5   0.1   0.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0 1.0E6     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     6    19    22    23    50   501   502
     0
```

```
SECTION   II:  NODE GENERATION
     1     1    28   1.0   0.0     0.0   0.0   0.0     1.0   0.0
   757     1   784   1.0   1.0     0.0   0.0   1.0     1.0   0.0
     1    28   757   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     2    28   758   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     3    28   759   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     4    28   760   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     5    28   761   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     6    28   762   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     7    28   763   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     8    28   764   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     9    28   765   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    10    28   766   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    11    28   767   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    12    28   768   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    13    28   769   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    14    28   770   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    15    28   771   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    16    28   772   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    17    28   773   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    18    28   774   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    19    28   775   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    20    28   776   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    21    28   777   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    22    28   778   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    23    28   779   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    24    28   780   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    25    28   781   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    26    28   782   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    27    28   783   1.0   0.0  -32767   0.0   1.0  -32767   0.0
    28    28   784   1.0   0.0  -32767   0.0   1.0  -32767   0.0
     0     0     0   0.0     0.0     0.0   0.0   0.0     0.0   0.0
SECTION  III:  ELEMENT GENERATION
     1    27   703     1   1.0      28    29    30       2     1
     2    27   704     1   1.0      28    30    31       3     2
```

```
      3     27    705      1    1.0     28     31     32      4      3
      4     27    706      1    1.0     28     32     33      5      4
      5     27    707      1    1.0     28     33     34      6      5
      6     27    708      1    1.0     28     34     35      7      6
      7     27    709      1    1.0     28     35     36      8      7
      8     27    710      1    1.0     28     36     37      9      8
      9     27    711      1    1.0     28     37     38     10      9
     10     27    712      1    1.0     28     38     39     11     10
     11     27    713      1    1.0     28     39     40     12     11
     12     27    714      1    1.0     28     40     41     13     12
     13     27    715      1    1.0     28     41     42     14     13
     14     27    716      1    1.0     28     42     43     15     14
     15     27    717      1    1.0     28     43     44     16     15
     16     27    718      1    1.0     28     44     45     17     16
     17     27    719      1    1.0     28     45     46     18     17
     18     27    720      1    1.0     28     46     47     19     18
     19     27    721      1    1.0     28     47     48     20     19
     20     27    722      1    1.0     28     48     49     21     20
     21     27    723      1    1.0     28     49     50     22     21
     22     27    724      1    1.0     28     50     51     23     22
     23     27    725      1    1.0     28     51     52     24     23
     24     27    726      1    1.0     28     52     53     25     24
     25     27    727      1    1.0     28     53     54     26     25
     26     27    728      1    1.0     28     54     55     27     26
     27     27    729      1    1.0     28     55     56     28     27
      0      0      0      0    0.0      0      0      0      0      0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
AIR
 0.0267  1.145  1.145    1007      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
1.87E-5      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
      0      0      0       0      0      0      0      0      0      0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
      0
   0.01
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
  1   1   28     1     1
 29  28  729     1     1
 56  28  756     1     1
757   1  784     1     1
 12   1   17     2     1
768   1  773     0     0
759   1  764     1     1
777   1  782     1     1
420  28  560     1     1
393  28  533     1     1
  0   0    0     0     0
INTER-ELEMENT RADIATION
  0    0    0    0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

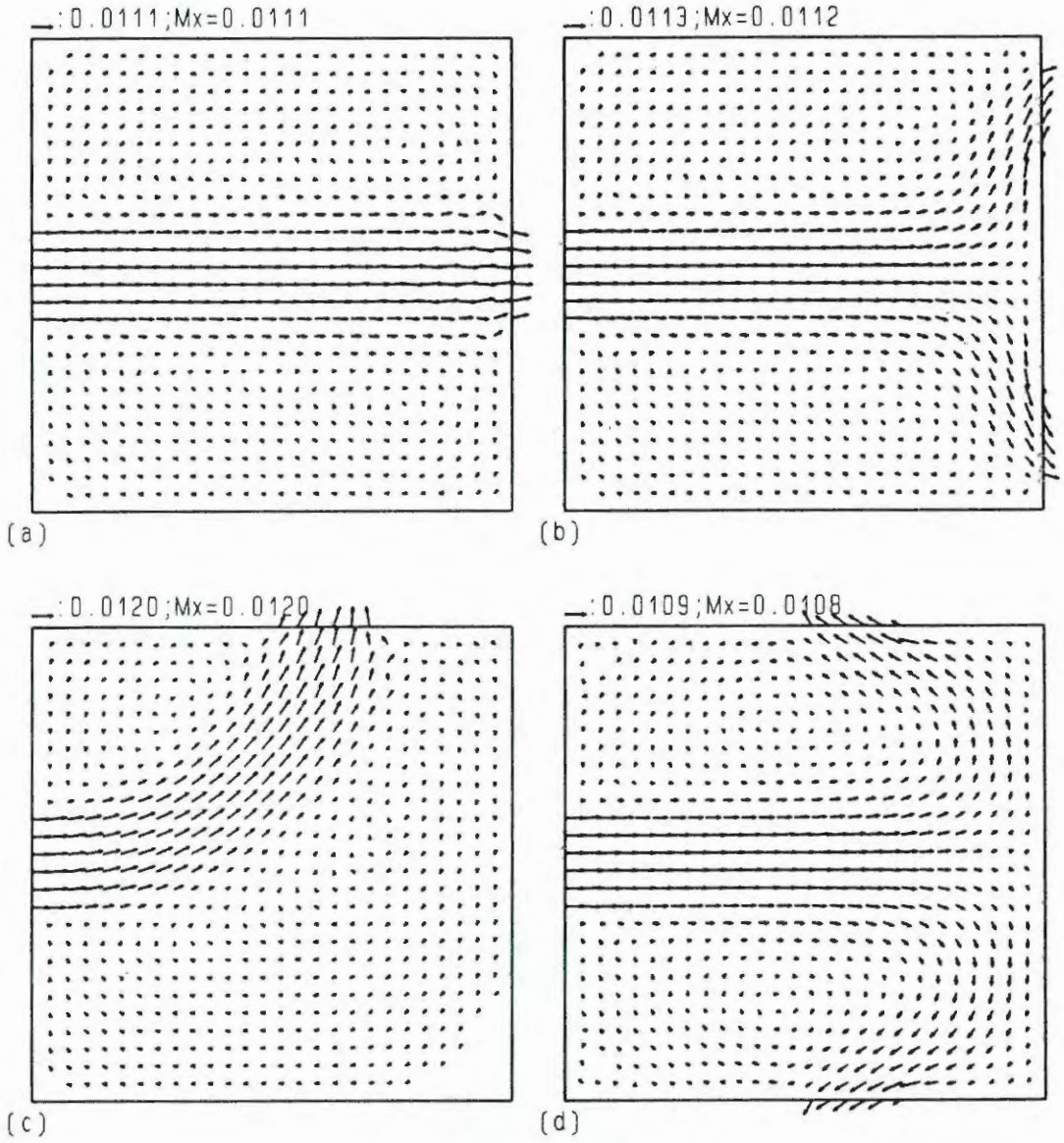


Figure 6-6 Velocity distribution in a ventilated room.

6.7 CONTAMINANT DISTRIBUTION IN A VENTILATED ROOM

In this example, the effect of various ventilation modes on contaminant distribution is studied. The same mesh used in the preceding example is employed. Throughout the simulations the same inlets are used. The velocity components and contaminant concentration are specified at the inlets. At the upper and lower inlets the contaminant concentration are assigned to be 10 units/m^3 and 0 units/m^3, respectively.

Figure 6-7.1 shows the velocity distributions for various ventilation configurations. The contaminant contours are given in Figure 6-7.2. The results shown in Figures 6-7.1 and 6-7.2 correspond to four different simulations. In these simulations the outlet boundary condition flags are modified.

```
EXAMPLE 7: CONTAMINANT DISTRIBUTION IN A VENTILATED ROOM.
   784   729     1     0     2     5
     0     0     0     0     0
     3     0     5
   1.0     0     2     1
     0     0
     3     1     2    16
     1   0.0   0.5   0.1   0.0
     2   0.0   0.5   0.1   0.0
    16   0.0   0.5   0.1   0.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0  1.0E6    0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     7    21    22    23    50   501   502   516
     0

SECTION   II:  NODE GENERATION
     1     1    28   1.0   0.0   0.0   0.0   0.0   1.0   0.0
   757     1   784   1.0   1.0   0.0   0.0   1.0   1.0   0.0
     1    28   757   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     2    28   758   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     3    28   759   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     4    28   760   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     5    28   761   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     6    28   762   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     7    28   763   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     8    28   764   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     9    28   765   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    10    28   766   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    11    28   767   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    12    28   768   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    13    28   769   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    14    28   770   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    15    28   771   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    16    28   772   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    17    28   773   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    18    28   774   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    19    28   775   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    20    28   776   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    21    28   777   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    22    28   778   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    23    28   779   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    24    28   780   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    25    28   781   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    26    28   782   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    27    28   783   1.0   0.0 -32767  0.0   1.0 -32767  0.0
    28    28   784   1.0   0.0 -32767  0.0   1.0 -32767  0.0
     0     0     0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
SECTION  III:  ELEMENT GENERATION
     1    27   703     1   1.0    28    29    30     2     1
```

```
     2    27   704    1   1.0   28   30   31    3    2
     3    27   705    1   1.0   28   31   32    4    3
     4    27   706    1   1.0   28   32   33    5    4
     5    27   707    1   1.0   28   33   34    6    5
     6    27   708    1   1.0   28   34   35    7    6
     7    27   709    1   1.0   28   35   36    8    7
     8    27   710    1   1.0   28   36   37    9    8
     9    27   711    1   1.0   28   37   38   10    9
    10    27   712    1   1.0   28   38   39   11   10
    11    27   713    1   1.0   28   39   40   12   11
    12    27   714    1   1.0   28   40   41   13   12
    13    27   715    1   1.0   28   41   42   14   13
    14    27   716    1   1.0   28   42   43   15   14
    15    27   717    1   1.0   28   43   44   16   15
    16    27   718    1   1.0   28   44   45   17   16
    17    27   719    1   1.0   28   45   46   18   17
    18    27   720    1   1.0   28   46   47   19   18
    19    27   721    1   1.0   28   47   48   20   19
    20    27   722    1   1.0   28   48   49   21   20
    21    27   723    1   1.0   28   49   50   22   21
    22    27   724    1   1.0   28   50   51   23   22
    23    27   725    1   1.0   28   51   52   24   23
    24    27   726    1   1.0   28   52   53   25   24
    25    27   727    1   1.0   28   53   54   26   25
    26    27   728    1   1.0   28   54   55   27   26
    27    27   729    1   1.0   28   55   56   28   27
     0     0     0    0   0.0    0    0    0    0    0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
AIR
 0.0267  1.145  1.145   1007    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
 9.1E-6      0      0      0    0    0    0    0    0    0
1.87E-5      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
      0      0      0      0    0    0    0    0    0    0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
      0
   0.01
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
  1   1   28     1     1     0
 29  28  729     1     1     0
 56  28  756     1     1     0
757   1  784     1     1     0
 21   1   26     2     1     2
  3   1    8     2     1     1
 12   1   17     1     1     0
768   1  773     0     0     0
759   1  764     1     1     0
777   1  782     1     1     0
420  28  560     1     1     0
393  28  533     1     1     0
  0   0    0     0     0     0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

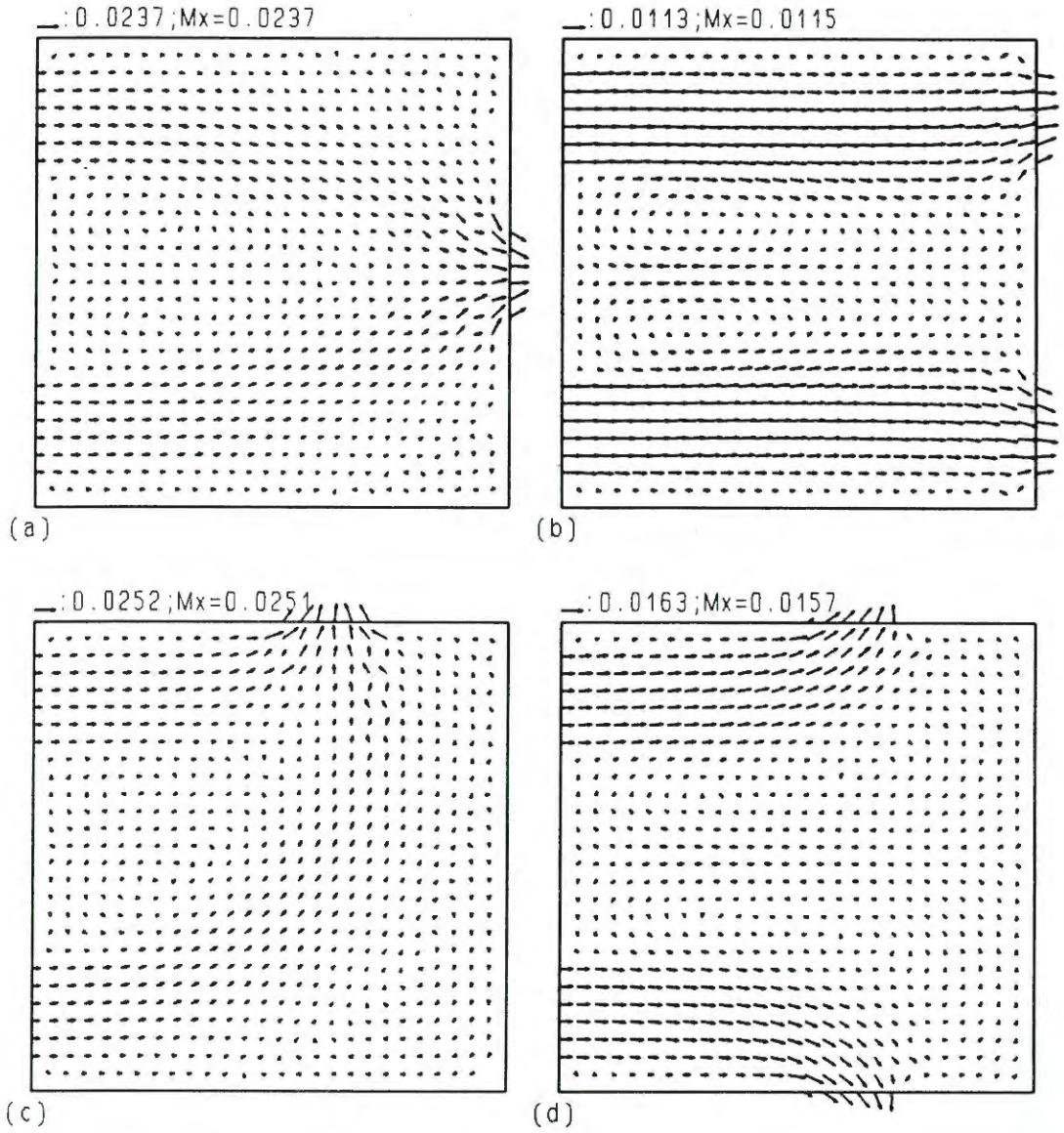


Figure 6-7.1 Velocity distribution in a ventilated room with two inlets.

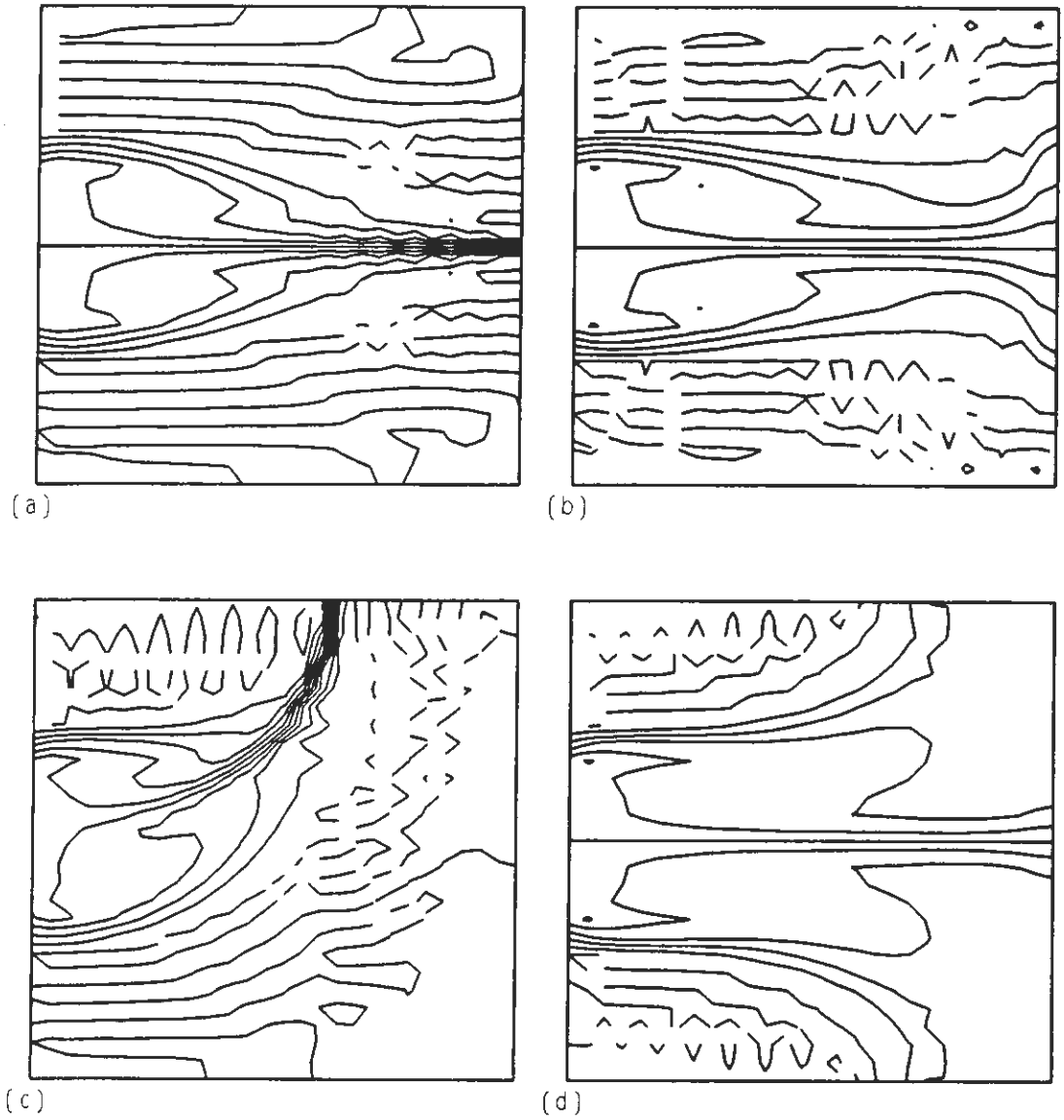
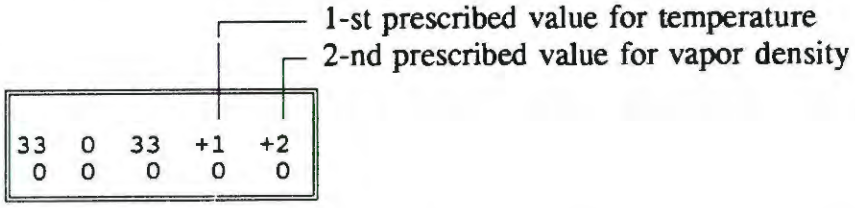


Figure 6-7.3 Contaminant flux distribution in a ventilated room.

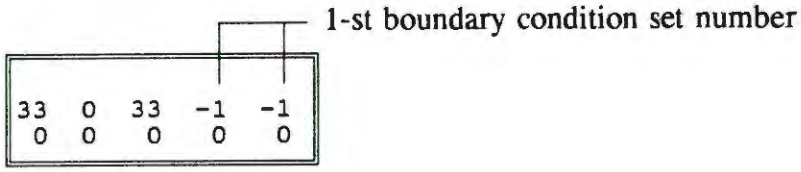
6.8 VALIDATION OF EVAPORATION AND CONDENSATION THEORY

In this example, the results from combined heat and moisture transfer simulation for a one-dimensional slab problem is compared with the closed form solutions. In the simulations a linearized sorption curve (U_e = $a+b\rho_v-cT$) and constant material properties are used. The closed form solutions are given by Dabir (1988) and Razzaq (1988). Three different simulations are performed by modifying the input files. In the modifications the boundary condition flag assigned to node number 33 is changed.

Case (a): Both temperature and vapor density values are prescribed at node 33. Therefore, the boundary condition flag generation data are specified as follows:



Case (b): Convective boundary conditions are used at node 33. Therefore, the boundary condition flag generation data are specified as follows:



Case (c): Imposed flux boundary conditions are used at node 33. Therefore, the boundary condition flag generation data are specified as follows:

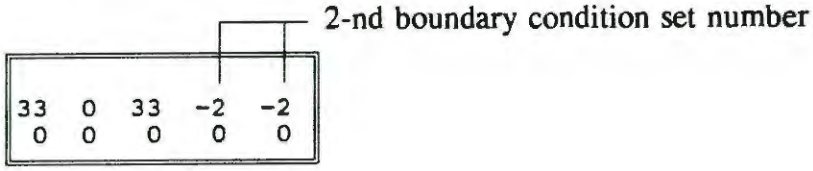


Figure 6-8.1 and 6-8.2 correspond to prescribed temperature and water vapor density. Figure 6-8.3 and 6-8.4 correspond to convective boundary

conditions for temperature and water vapor density, respectively. Figure 6-8.5 and 6-8.6 correspond to imposed heat and moisture fluxes, respectively.

```
EXAMPLE 8: VALIDATION OF "EVAPORATION AND CONDENSATION" THEORY.
    33    32      1     2     2     1
     1     1      0   0.1    24
     2     0      0
   1.0     0      2     0
     0     0
     2    10     13
    10   300    1.0   0.0   0.6
    13 0.012    1.0   0.0   0.6
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     0     0      0     0     0     0     0     0     0     0
     4    23     50   510   513
     1
     0   0.1     24
```

```
SECTION   II:  NODE GENERATION
     1     1    33   1.0   0.0     0.0     0.0     0.1     0.0     0.0
     0     0     0   1.0   0.0     0.0     0.0     0.0     0.0     0.0
SECTION  III:  ELEMENT GENERATION
     1     1    32     1   1.0       1       1       2
     0     0     0     0     0       0       0       0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
GYPSUM
  0.262 725 725   1085        0       0       0       0       0       0
 5.5E-6   0 0.7 1.1602 8.794E-4 0.01065 8.80179 0.06152 0.33108 2.5E+6
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
      0   0   0      0        0       0       0       0       0       0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
B.C. SET NUMBER 1
    5.0  305        0   0   0       0       0       0       0       0
7.347E-5 0.016      0   0   0       0       0       0       0       0
      0     0       0   0   0       0       0       0       0       0
      0     0       0   0   0       0       0       0       0       0
B.C. SET NUMBER 2
      0     0      10   0   0       0       0       0       0       0
      0     0 2.78E-8   0   0       0       0       0       0       0
      0     0       0   0   0       0       0       0       0       0
      0     0       0   0   0       0       0       0       0       0
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
    305
  0.016
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
     33     0    33     1     2
```

```
      0     0     0     0     0
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
      0     0     0     0
SECTION    X:  POINT SOURCE SPECIFICATION
      0
```

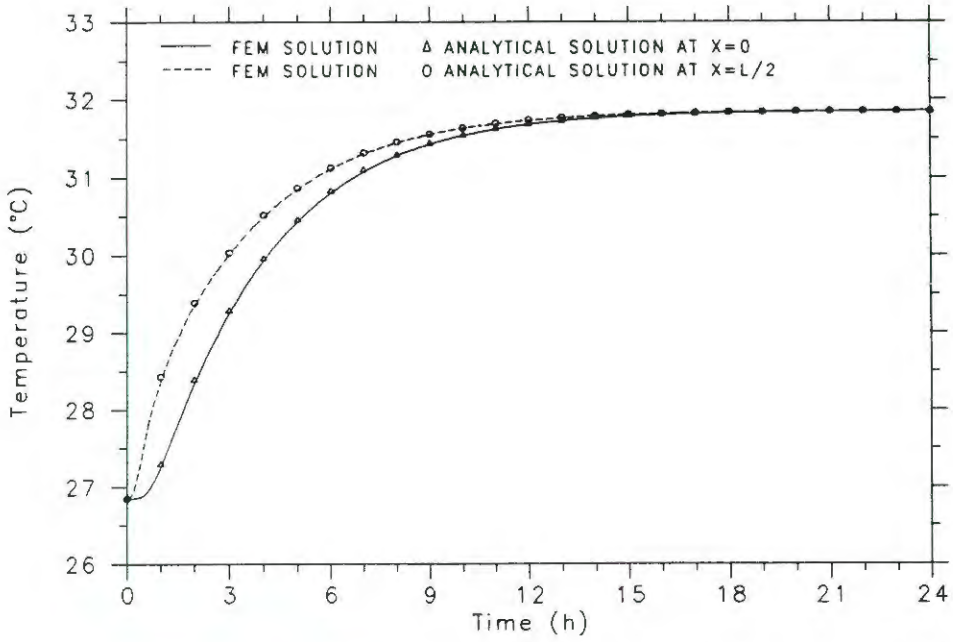


Figure 6-8.1 Comparison of analytical versus finite element temperature distribution in a gypsum drywall sample exposed to prescribed boundary conditions.

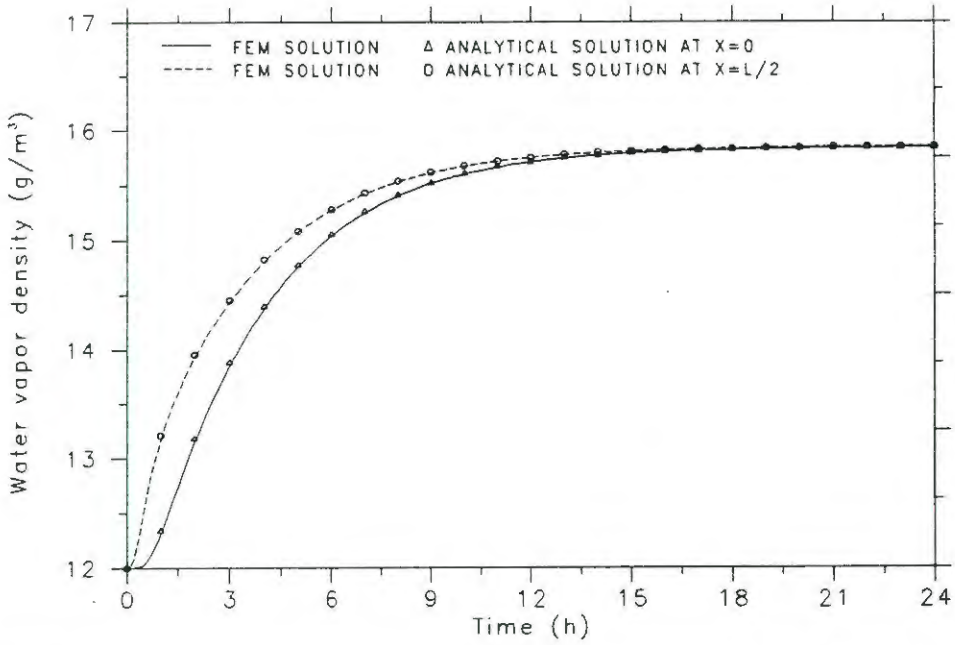


Figure 6-8.2 Comparison of analytical versus finite element vapor density distribution in a gypsum drywall sample exposed to prescribed boundary conditions.

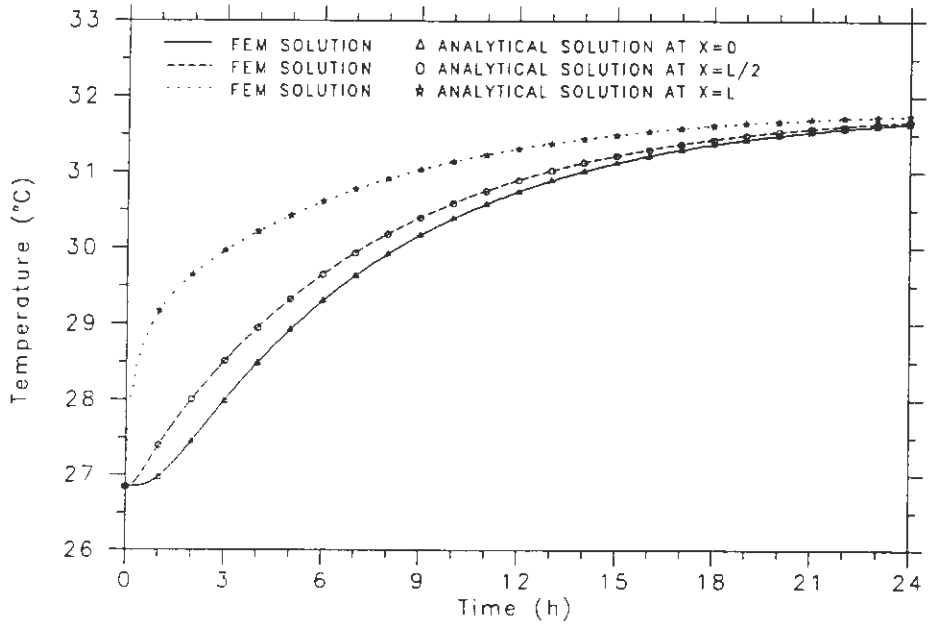


Figure 6-8.3 Comparison of analytical versus finite element temperature distribution in a gypsum drywall sample exposed to convective boundary conditions.

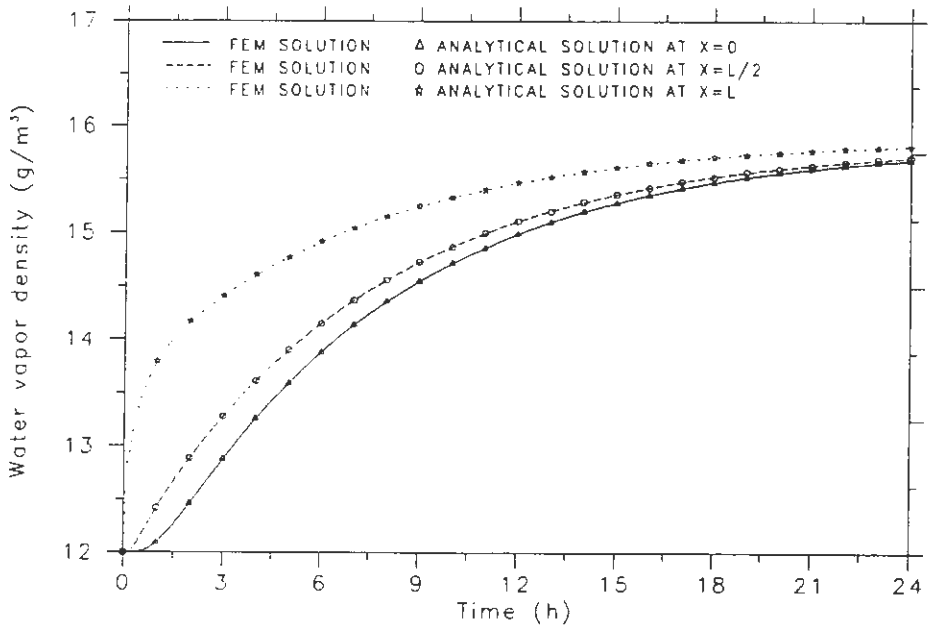


Figure 6-8.4 Comparison of analytical versus finite element vapor density distribution in a gypsum drywall sample exposed to convective boundary conditions.

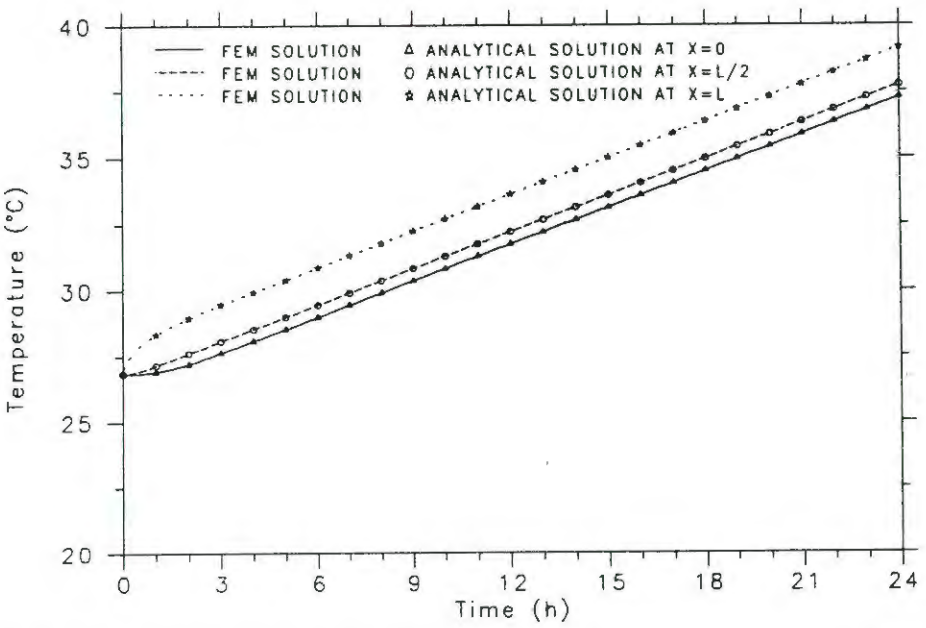


Figure 6-8.5 Comparison of analytical versus finite element temperature distribution in a gypsum drywall sample exposed to imposed flux boundary conditions.

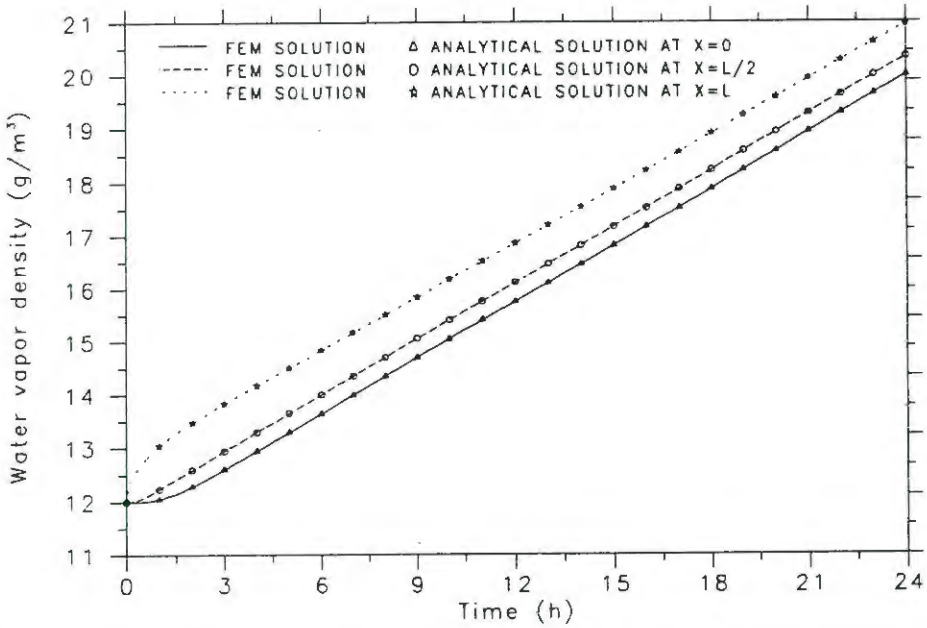


Figure 6-8.6 Comparison of analytical versus finite element vapor density distribution in a gypsum drywall sample exposed to imposed flux boundary conditions.

6.9 RADON TRANSPORT IN SOIL-SLAB COMPOSITE

In this example, Radon transport and diffusion in a two-dimensional soil-slab composite is simulated. The governing equations of pressure and Radon concentration are shown in Subsection 5.9. The geometry is composed of concrete slab (indoor condition), concrete wall foundation and soil. The top soil surface is assumed as outdoor condition. The crack is located between the concrete slab and wall foundation. The soli is assumed to be deep enough to have insulated boundary conditions for pressure and Radon concentration at the subsurface. The exposed slab surface is assumed to be at a pressure of -2.4 Pa and a radon concentration level of 54 Bq/m^3. Both, the pressure and Radon at the exposed soil surface are assumed to be zero. In addition, the vertical boundaries are assumed to be impermeable to both, air flow and Radon flux. The initial conditions are set to zero for both pressure and radon concentration.

```
PRESSURE AND RADON CONCENTRATION EQUATION TEST (NO. 25 AND 26)
   468   422     3     0     3     5
     1     0     0     1    24
     1     0    50
   1.0     0     2     0
     0     0
     2    25    26
    25     0   1.0   0.1   1.0
    26     0   1.0   0.1   1.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
  0.26 1.8E-5 2.1E-6   0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     6    19    22    23    50   525   526
     1
     0     1    24
```

```
SECTION    II: NODE GENERATION
      1      1     17    1.0     0.0  7.2644    0.0  4.877  7.2644    0.0
     17      1     19    1.0   4.877  7.2644    0.0  4.897  7.2644    0.0
     19      1     20    1.0   4.897  7.2644    0.0  5.202  7.2644    0.0
     21      1     37    1.0     0.0  7.1629    0.0  4.877  7.1629    0.0
     37      1     39    1.0   4.877  7.1629    0.0  4.897  7.1629    0.0
     39      1     40    1.0   4.897  7.1629    0.0  5.202  7.1629    0.0
     40      1     52    1.0   5.202  7.1629    0.0  8.555  7.1629    0.0
     53      1     69    1.0     0.0  7.0105    0.0  4.877  7.0105    0.0
     69      1     71    1.0   4.877  7.0105    0.0  4.897  7.0105    0.0
     71      1     72    1.0   4.897  7.0105    0.0  5.202  7.0105    0.0
     72      1     84    1.0   5.202  7.0105    0.0  8.555  7.0105    0.0
     85      1    101    1.0     0.0  6.7057    0.0  4.877  6.7057    0.0
    101      1    103    1.0   4.877  6.7057    0.0  4.897  6.7057    0.0
    103      1    104    1.0   4.897  6.7057    0.0  5.202  6.7057    0.0
    104      1    116    1.0   5.202  6.7057    0.0  8.555  6.7057    0.0
    117      1    133    1.0     0.0  6.4009    0.0  4.877  6.4009    0.0
    133      1    135    1.0   4.877  6.4009    0.0  4.897  6.4009    0.0
    135      1    136    1.0   4.897  6.4009    0.0  5.202  6.4009    0.0
    136      1    148    1.0   5.202  6.4009    0.0  8.555  6.4009    0.0
    149      1    165    1.0     0.0  6.0961    0.0  4.877  6.0961    0.0
    165      1    167    1.0   4.877  6.0961    0.0  4.897  6.0961    0.0
    167      1    168    1.0   4.897  6.0961    0.0  5.202  6.0961    0.0
    168      1    180    1.0   5.202  6.0961    0.0  8.555  6.0961    0.0
    181      1    197    1.0     0.0  5.7913    0.0  4.877  5.7913    0.0
    197      1    199    1.0   4.877  5.7913    0.0  4.897  5.7913    0.0
    199      1    200    1.0   4.897  5.7913    0.0  5.202  5.7913    0.0
    200      1    212    1.0   5.202  5.7913    0.0  8.555  5.7913    0.0
    213      1    229    1.0     0.0  5.4865    0.0  4.877  5.4865    0.0
    229      1    231    1.0   4.877  5.4865    0.0  4.897  5.4865    0.0
    231      1    232    1.0   4.897  5.4865    0.0  5.202  5.4865    0.0
    232      1    244    1.0   5.202  5.4865    0.0  8.555  5.4865    0.0
    245      1    261    1.0     0.0  4.8779    0.0  4.877  4.8779    0.0
    261      1    263    1.0   4.877  4.8779    0.0  4.897  4.8779    0.0
```

```
   263     1    264    1.0   4.897   4.8779    0.0   5.202   4.8779    0.0
   264     1    276    1.0   5.202   4.8779    0.0   8.555   4.8779    0.0
   277     1    293    1.0     0.0   4.2673    0.0   4.877   4.2673    0.0
   293     1    295    1.0   4.877   4.2673    0.0   4.897   4.2673    0.0
   295     1    296    1.0   4.897   4.2673    0.0   5.202   4.2673    0.0
   296     1    308    1.0   5.202   4.2673    0.0   8.555   4.2673    0.0
   309     1    325    1.0     0.0   3.6577    0.0   4.877   3.6577    0.0
   325     1    327    1.0   4.877   3.6577    0.0   4.897   3.6577    0.0
   327     1    328    1.0   4.897   3.6577    0.0   5.202   3.6577    0.0
   328     1    340    1.0   5.202   3.6577    0.0   8.555   3.6577    0.0
   341     1    357    1.0     0.0   2.7432    0.0   4.877   2.7432    0.0
   357     1    359    1.0   4.877   2.7432    0.0   4.897   2.7432    0.0
   359     1    360    1.0   4.897   2.7432    0.0   5.202   2.7432    0.0
   360     1    372    1.0   5.202   2.7432    0.0   8.555   2.7432    0.0
   373     1    389    1.0     0.0   1.8288    0.0   4.877   1.8288    0.0
   389     1    391    1.0   4.877   1.8288    0.0   4.897   1.8288    0.0
   391     1    392    1.0   4.897   1.8288    0.0   5.202   1.8288    0.0
   392     1    404    1.0   5.202   1.8288    0.0   8.555   1.8288    0.0
   405     1    421    1.0     0.0   0.9145    0.0   4.877   0.9145    0.0
   421     1    423    1.0   4.877   0.9145    0.0   4.897   0.9145    0.0
   423     1    424    1.0   4.897   0.9145    0.0   5.202   0.9145    0.0
   424     1    436    1.0   5.202   0.9145    0.0   8.555   0.9145    0.0
   437     1    453    1.0     0.0   0.0000    0.0   4.877   0.0000    0.0
   453     1    455    1.0   4.877   0.0000    0.0   4.897   0.0000    0.0
   455     1    456    1.0   4.897   0.0000    0.0   5.202   0.0000    0.0
   456     1    468    1.0   5.202   0.0000    0.0   8.555   0.0000    0.0
     0     0      0    0.0     0.0      0.0    0.0     0.0      0.0    0.0
SECTION  III:  ELEMENT GENERATION
     1     1     16     1    1.0      1    022    002    001    021
    17     1     18     3    1.0      1    038    018    017    037
    19     0     19     1    1.0      1    040    020    019    039
    20     1     37     2    1.0      1    054    022    021    053
    38     0     38     1    1.0      1    072    040    039    071
    39     1     50     2    1.0      1    073    041    040    072
    51     1     68     2    1.0      1    086    054    053    085
    69     0     69     1    1.0      1    104    072    071    103
    70     1     81     2    1.0      1    105    073    072    104
    82     1    112     2    1.0      1    118    086    085    117
   113     1    143     2    1.0      1    150    118    117    149
   144     1    174     2    1.0      1    182    150    149    181
   175     1    205     2    1.0      1    214    182    181    213
   206     1    236     2    1.0      1    246    214    213    245
   237     1    267     2    1.0      1    278    246    245    277
   268     1    298     2    1.0      1    310    278    277    309
   299     1    329     2    1.0      1    342    310    309    341
   330     1    360     2    1.0      1    374    342    341    373
   361     1    391     2    1.0      1    406    374    373    405
   392     1    422     2    1.0      1    438    406    405    437
     0     0      0     0    0.0      0      0      0      0      0
SECTION   IV:  MATERIAL PROPERTY SPECIFICATION
<1> CONCRETE
     0     0   2160       0      0      0      0      0      0      0
     0     0    0.2       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
1.12E-5 0.1E-3    12 1.0E-15 11.11    0.0    .25   1.8E4    0.1  3.0E-6
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
<2> SAND
     0     0   1600       0      0      0      0      0      0      0
     0     0  0.407       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
     0     0      0       0      0      0      0      0      0      0
```

```
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
1.12E-5 0.358E-3   12 2.18E-11 37.03   0.0   .25   1.8E4 0.213 4.44E-4
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
<3> AIR
     0      0   1.18       0     0     0     0     0     0     0
     0      0    0.4       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
1.12E-3 0.1E-3     12 5.0E-10 0.000   0.0   .25   1.8E4   0.1  3.0E-6
     0      0      0       0     0     0     0     0     0     0
     0      0      0       0     0     0     0     0     0     0
SECTION    V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
SECTION   VI:  PRESCRIBED VALUE SPECIFICATION
-2.4
 0.0
 54.0
SECTION  VII:  BOUNDARY CONDITION FLAG GENERATION
     1     1    20     1     3
    41     1    52     2     2
     0     0     0     0     0
SECTION   IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
     0     0     0     0
SECTION    X:  POINT SOURCE SPECIFICATION
     0
```

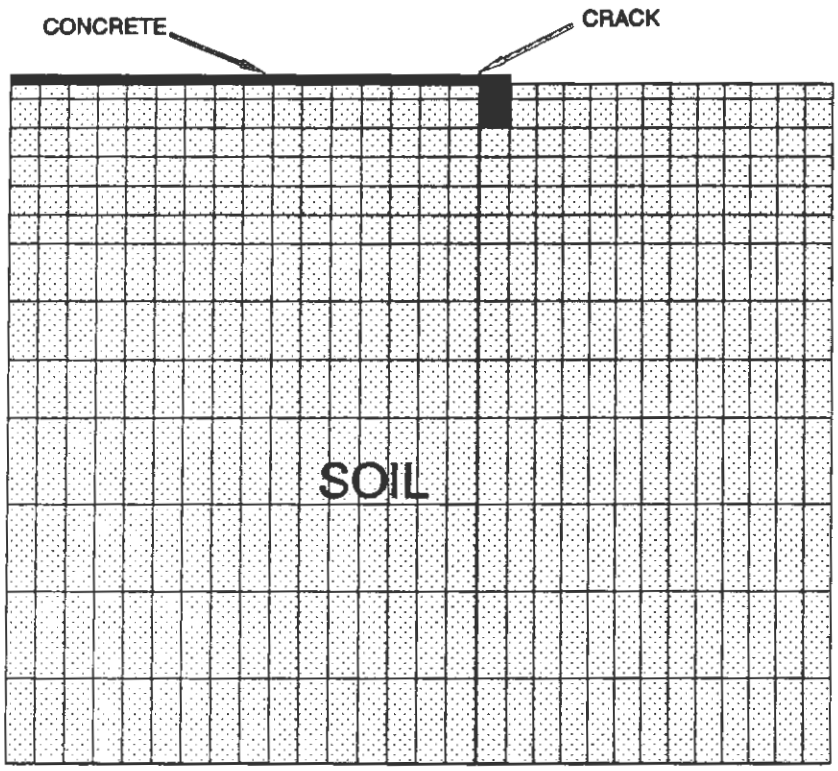


Figure 6-9.1 Mesh used in Radon transport simulation.

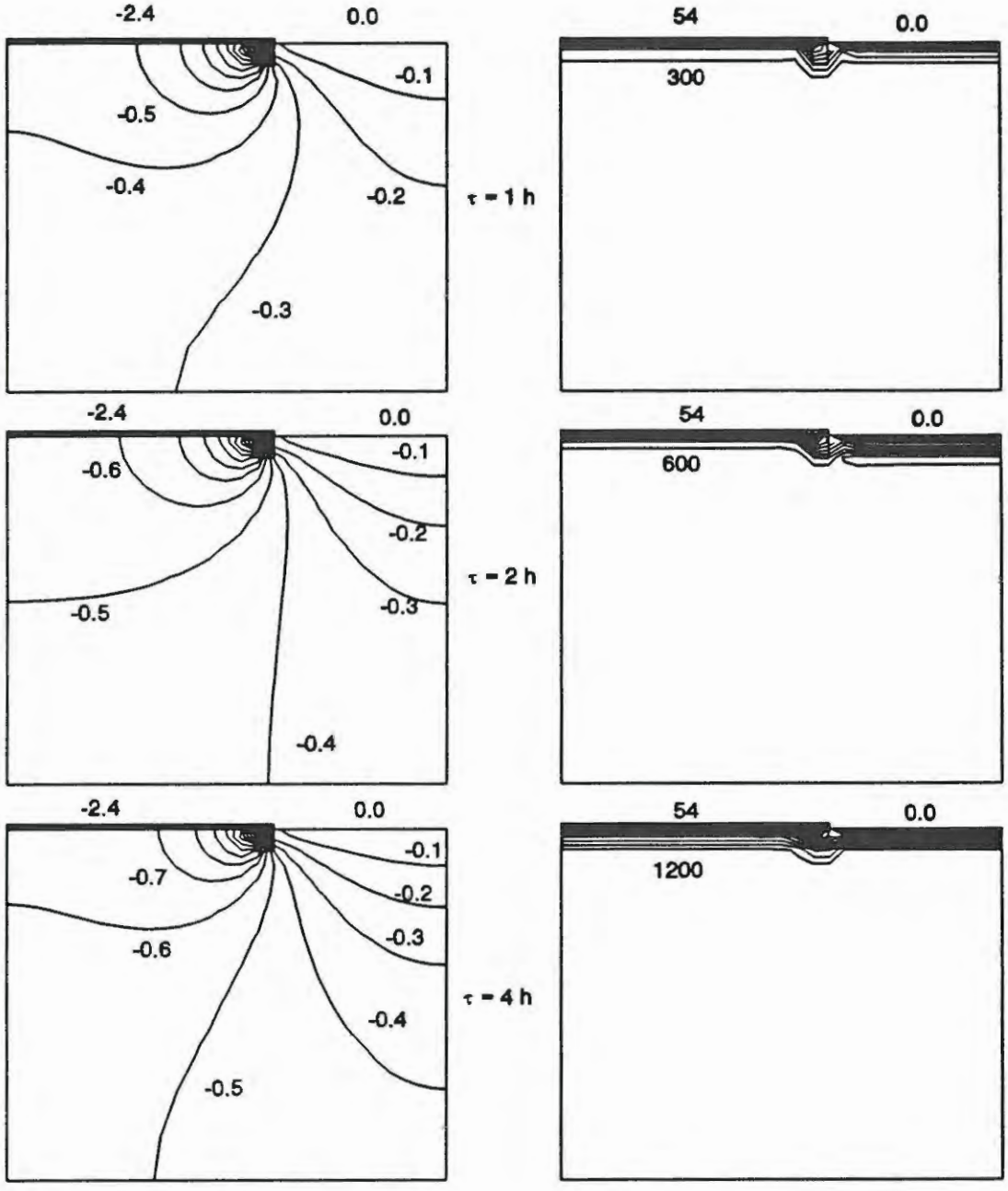


Figure 6-9.2 Pressure (left) and Radon (right) distributions and histories for Radon transport simulation.

6.10 HEAT TRANSFER IN A PHASE CHANGE MATERIAL

Certain materials (eg. mixture of fatty acids) exhibit the behavior of changing phase over a finite range of temperature, rather than at a distinct temperature. One way to model this behavior is to introduce a temperature dependent specific heat through the user defined subroutine VRPROP. An exponential curve-fit representative of the specific heat variation in a typical mixture of fatty acids is incorporated in VRPROP. The equation used is as follows:

$$C_p(T) = C_o + C_{max} \times \exp\left[-0.5 \times \left(\frac{T-C_1}{C_2}\right)^2\right]$$

where

C_p	Specific heat
C_o	Specific heat outside the phase change region
C_{max}	Peak specific heat in the transition region
C_1	Temperature at which the peak occurs
C_2	Parameter indicating the spread of the transition region

A gypsum wall board impregnated with phase change material is simulated in this example. The wall, initially at 290 K, is assumed to be insulated on one side and exposed to convection (330 K) on the other. The constants C_o (1085 J/kg.K), C_{max} (40,000 - 140,000 J/kg.K) and C_1 (297.6 K) and C_2 (0.35 - 0.1) are input to the program through CON(31), CON(32), CON(33) and CON(34), respectively. The value of specific heat, PRO(4), is set to -1005 in order to invoke this variable property through VRPROP. Figure 6-10 shows the results of this simulation. The constants used in the simulations are given in the figures.

```
EXAMPLE 10: HEAT TRANSFER IN A PHASE CHANGE MATERIAL.
     13     12      1      1      0      1
     -1      1      0    0.1     24
      1      0     50
    1.0      0      2      0
      0      0
      1     10
     10    290    0.5    0.1    0.6
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
   1085  14.E5  297.6   0.01      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      0      0      0      0      0      0      0      0      0      0
      4     19     23     50    510
      1
      0    0.1     24




SECTION    II:  NODE GENERATION
      1       1      13     1.0     0.0     0.0     0.0 0.0125    0.0     0.0
      0       0       0     0.0     0.0     0.0     0.0    0.0    0.0     0.0
SECTION   III:  ELEMENT GENERATION
      1       1      12       1     1.0       1       1      2
      0       0       0       0     0.0       0       0      0
SECTION    IV:  MATERIAL PROPERTY SPECIFICATION
GYPSUM
  0.262   725     725  -1013     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
SECTION     V:  BOUNDARY CONDITION SET VALUE SPECIFICATION
B.C. SET NUMBER 1
    5.0   300       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
      0     0       0      0     0      0      0      0      0      0
SECTION    VI:  PRESCRIBED VALUE SPECIFICATION
SECTION   VII:  BOUNDARY CONDITION FLAG GENERATION
     13     0      13     -1
      0     0       0      0
SECTION    IX:  INTER-ELEMENT RADIATION SURFACE GENERATION
      0     0       0      0
SECTION     X:  POINT SOURCE SPECIFICATION
      0
```

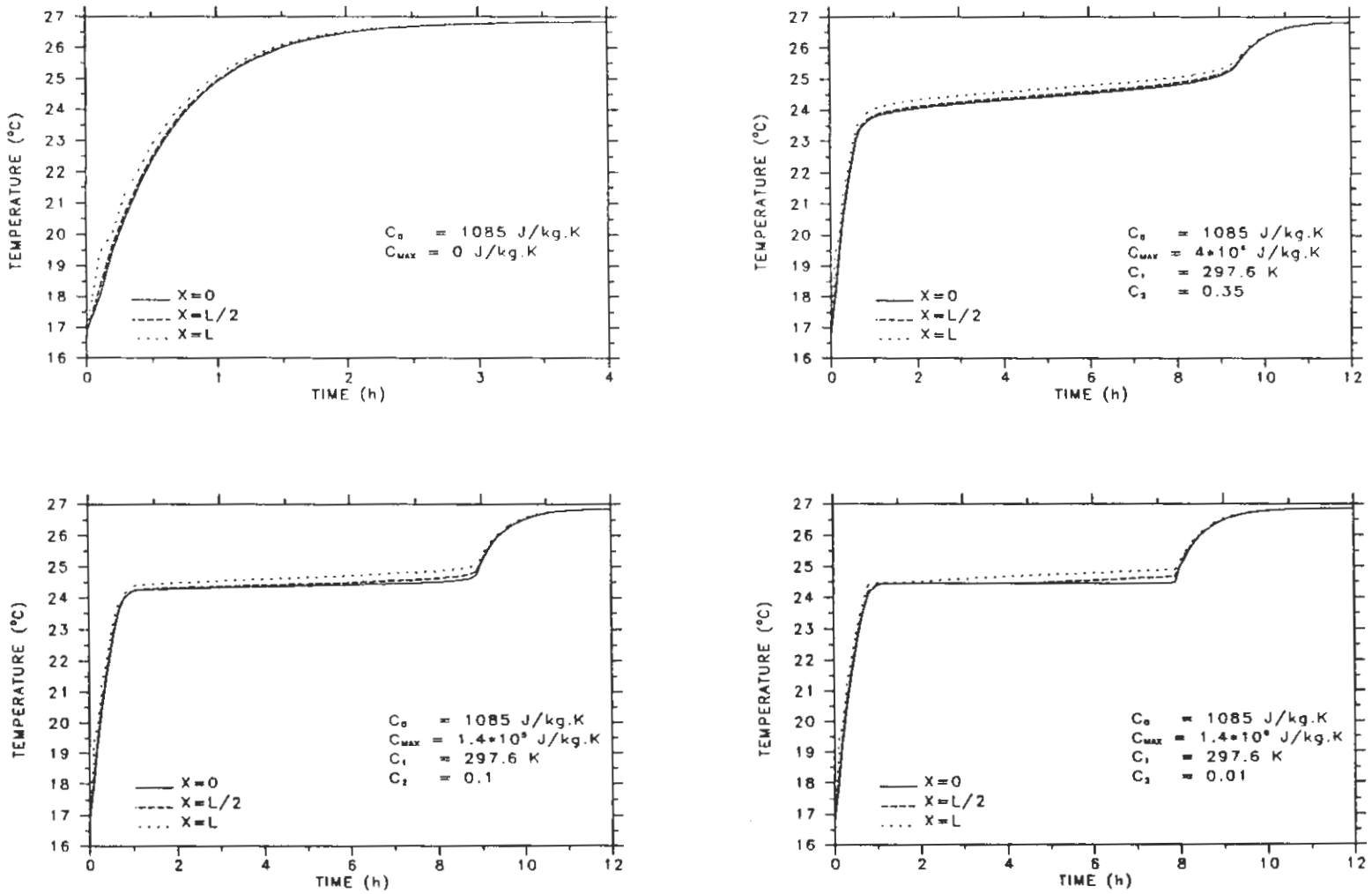


Figure 6-10 Temperature distribution in a gypsum drywall impregnated with phase change material.

6.11 COMBINED HEAT AND MASS TRANSFER IN BUILDING USING EMPD

In this example, a residential building is simulated using the Effective Moisture Penetration Depth (EMPD) theory. The building is assumed to consist of two zones, a conditioned living space and an unconditioned attic. Each wall component is discretized using a quartic element (3 internal nodes and 2 interface nodes). Figure 6-11.1 shows the wall configurations and surface node numbers. The input decks supplied in this section must be studied along with Figure 6-11.1.

The spatially distributed energy equation is solved to get the temperature distributions in the walls. However, the spatially lumped EMPD equations are solved to simulate the moisture adsorption and desorption of the inner wall surfaces. The exterior surfaces of the walls are exposed to ambient conditions corresponding to a typical July day in Miami. A listing of the ambient file is given in the following pages. In the simulations the loads are assumed to be due to infiltration, internal heat and moisture generation and conduction through the walls. A typical mechanical cooling unit is used to remove the loads. The thermostat is set to 25.55°C. The performance of the mechanical unit is assumed to be a function of indoor conditions and ambient dry-bulb temperature.

It is important to note that, in this simulation three input files are utilized. The first input file is used by the main program. The second and third input files that contain the building description and the ambient data are used by the building program. In Line 28 of the first input file, the input data file name ZONE11.DAT is used to indicate the name of the data file that contains the building information. Similarly, in ZONE11.DAT, MIAMI.DAT is used to indicate the name of the file that contains the environmental data.

The indoor conditions and associated loads are shown in Figure 6-11.2.

```
EXAMPLE 11. COMBINED HEAT AND MASS TRANSFER IN BUILDINGS USING EMPD.
    119    27     8     4     1     4
      1     0     0   1.0   240   1.0
      1     0   200
    1.0     0     5     0
      0     0
      1    10
     10   300   0.8  0.01   1.0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
5.67E-8     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      0     0     0     0     0     0     0     0     0     0
      3    19   260   510
      1
      1     0   240
```

```
ZONE11.DAT
NODE GENERATION
      1     1     5     1   0.00000   0.0   0.0   0.01111   0.0   0.0
      5     1     9     1   0.01111   0.0   0.0   0.09366   0.0   0.0
      9     1    13     1   0.09366   0.0   0.0   0.10636   0.0   0.0
     14     1    18     1   0.00000   0.0   0.0   0.01111   0.0   0.0
     18     1    22     1   0.01111   0.0   0.0   0.09366   0.0   0.0
     22     1    26     1   0.09366   0.0   0.0   0.10636   0.0   0.0
     27     1    31     1   0.00000   0.0   0.0   0.01111   0.0   0.0
     31     1    35     1   0.01111   0.0   0.0   0.09366   0.0   0.0
     35     1    39     1   0.09366   0.0   0.0   0.10636   0.0   0.0
     40     1    44     1   0.00000   0.0   0.0   0.01111   0.0   0.0
     44     1    48     1   0.01111   0.0   0.0   0.09366   0.0   0.0
     48     1    52     1   0.09366   0.0   0.0   0.10636   0.0   0.0
     53     1    57     1   0.00000   0.0   0.0   0.02540   0.0   0.0
     58     1    66     1   0.00000   0.0   0.0   0.14859   0.0   0.0
     66     1    70     1   0.14859   0.0   0.0   0.16129   0.0   0.0
     71     1    75     1   0.00000   0.0   0.0   0.01270   0.0   0.0
     75     1    83     1   0.01270   0.0   0.0   0.11430   0.0   0.0
     83     1    91     1   0.11430   0.0   0.0   0.42270   0.0   0.0
     92     1    96     1   0.00000   0.0   0.0   0.02540   0.0   0.0
     96     1   100     1   0.02540   0.0   0.0   0.05080   0.0   0.0
    101     1   105     1   0.00000   0.0   0.0   0.02540   0.0   0.0
    105     1   109     1   0.02540   0.0   0.0   0.05080   0.0   0.0
    110     1   114     1   0.00000   0.0   0.0   0.02540   0.0   0.0
    115     1   119     1   0.00000   0.0   0.0   0.02540   0.0   0.0
      0     0     0     0   0.00000   0.0   0.0   0.00000   0.0   0.0
ELEMENT GENERATION
      1     0     1     1   37.160   1     1   5   2   3   4
      2     0     2     2   37.160   1     5   9   6   7   8
      3     0     3     3   37.160   1     9  13  10  11  12
      4     0     4     1   22.300   1    14  18  15  16  17
      5     0     5     2   22.300   1    18  22  19  20  21
      6     0     6     3   22.300   1    22  26  23  24  25
      7     0     7     1   37.160   1    27  31  28  29  30
      8     0     8     2   37.160   1    31  35  32  33  34
```

```
   9     0     9     3   37.160  1    35   39   36   37   38
  10     0    10     1   22.300  1    40   44   41   42   43
  11     0    11     2   22.300  1    44   48   45   46   47
  12     0    12     3   22.300  1    48   52   49   50   51
  13     0    13     3   104.00  1    53   57   54   55   56
  14     1    15     2   139.35  4    58   62   59   60   61
  16     0    16     3   139.35  1    66   70   67   68   69
  17     0    17     4   139.35  1    71   75   72   73   74
  18     1    19     5   139.35  4    75   79   76   77   78
  20     1    21     6   139.35  4    83   87   84   85   86
  22     0    22     7   80.448  1    92   96   93   94   95
  23     0    23     8   80.448  1    96  100   97   98   99
  24     0    24     7   80.448  1   101  105  102  103  104
  25     0    25     8   80.448  1   105  109  106  107  108
  26     0    26     8   12.069  1   110  114  111  112  113
  27     0    27     8   12.069  1   115  119  116  117  118
   0     0     0     0     0     0     0    0    0    0    0
MATERIAL PROPERTY SPECIFICATION
<1> MASONITE
  0.10560  800  800 1299 0.9  0.7500  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
<2> FIBERGLASS INSULATION
  0.04600   65   65  712 .93  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
<3> GYPSUM DRYWALL
  0.21600  720  720 1340 0.9  0.4000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0725  0.3970  7.77E-3 11.706  2.4E+6
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
<4> CARPET
  0.05900  250  250 1520 0.9  0.4000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  8.44E-3 9.3880  6.31E-3 1.3590  2.4E+6
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
<5> CONCRETE
  0.13000 2370 2370  880 0.9  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
```

```
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
 <6> DIRT
   0.86550 1600 1600  838   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
 <7> SHINGLE
   1.73060 1922 1922 1004 0.9  0.7500  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
 <8> PLYWOOD
   0.01200  600  600 1215 .75  0.7500  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
   0.00000    0    0    0   0  0.0000  0.0000  0.0000  0.0000  0.0000
 BOUNDARY CONDITION SET VALUE SPECIFICATION
 BC-1 heat transfer horizontally to zone
     8.289      0   0    0    0    0    0    0    0    0
     7.08E-3    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
 BC-2 heat transfer upward to zone
     9.256      0   0    0    0    0    0    0    0    0
     7.08E-3    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
 BC-3 heat transfer downward to zone
     2.256      0   0    0    0    0    0    0    0    0
     7.08E-3    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
 BC-4 heat transfer to ambient
      22.916    0   0    0    0    0    0    0    0    0
     7.08E-3    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
           0    0   0    0    0    0    0    0    0    0
 PRESCRIBED VALUE SPECIFICATION
    299.04
 BOUNDARY CONDITION FLAG GENERATION
       1     0     1    -4     0
      13     0    13    -1     0
      14     0    14    -4     0
      26     0    26    -1     0
```

```
    27     0    27    -4    0
    39     0    39    -1    0
    40     0    40    -4    0
    52     0    52    -1    0
    53     0    53    -1    0
    57     0    57    -1    0
    58     0    58    -2    0
    70     0    70    -3    0
    71     0    71    -2    0
    91     0    91    +1    0
    92     0    92    -4    0
   100     0   100    -3    0
   101     0   101    -4    0
   109     0   109    -3    0
   110     0   110    -4    0
   114     0   114    -1    0
   115     0   115    -4    0
   119     0   119    -1    0
     0     0     0     0    0
INTER-ELEMENT RADIATION SURFACE GENERATION
     0     0     0     0
POINT SOURSE
     0
```

```
EXAMPLE 11. BUILDING DATA FOR "EMPD" EXAMPLE
    2      3      22     1      1     0
    0      2       1     2
  201     24     205    24   1.0
 1.18   1007   2.4E6     0      0     0     0     0     0     0
7.0E3      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
    0      0       0     0      0     0     0     0     0     0
  +31    +32     +33   +34    +35   -36   -37   -38   -39   -40
SCHEDULES
INFILTRATION IN LIVING ZONE
 0.60  0.60  0.60  0.60  0.60  0.60  0.60  1.20  1.20  0.60  0.60  0.60
 0.60  0.60  0.60  1.20  1.20  1.20  1.20  0.60  0.60  0.60  0.60  0.60
INFILTRATION IN ATTIC
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
GAIN
 0.30  0.30  0.30  0.30  0.33  0.43  0.43  0.43  0.56  0.29  0.56  0.32
 0.24  0.24  0.48  0.48  0.70  0.70  0.77  0.77  1.00  0.43  0.29  0.30
ENVIRONMENTAL DATA
 55   25.8    80.25   0.2    0    3
MIAMI.DAT
BOUNDARY CONDITION MODIFICATION
   1   -1  180.0    90.0    37.16   0.000
  13    1  180.0    90.0    37.16   0.004
  14   -1  -90.0    90.0    22.30   0.000
  26    1  -90.0    90.0    22.30   0.004
  27   -1    0.0    90.0    37.16   0.000
  39    1    0.0    90.0    37.16   0.004
  40   -1   90.0    90.0    22.30   0.000
  52    1   90.0    90.0    22.30   0.004
  53    1    0.0    90.0   104.00   0.004
  57    1    0.0    90.0   104.00   0.004
  58    2    0.0     0.0   139.35   0.000
  70    1    0.0   180.0   139.35   0.004
  71    1    0.0     0.0   139.35   0.004
  91   -1    0.0     0.0   139.35   0.000
  92   -1    0.0    30.0   80.448   0.000
 100    2    0.0   150.0   80.448   0.000
 101   -1  180.0    30.0   80.448   0.000
 109    2  180.0   150.0   80.448   0.000
 110   -2  -90.0    90.0   12.069   0.000
 114    2  -90.0    90.0   12.069   0.000
 115   -2   90.0    90.0   12.069   0.000
 119    2   90.0    90.0   12.069   0.000
SYSTEM PARAMETERS
   0
ZONE DATA
 LIVING ROOM (ZONE 1)
    334   298.7  0.014
1793.3      3      0      0    0.6171
     0      0      0
   1.0      1      0
     0      0      0      0
     0      0      0      0
     0      0      0
298.70      0      0
273.15      0      0
  1.00      0      0
  0.00      0      0
     0      0
     2      0
     0      0      0      0
```

```
ATTIC (ZONE 2)
   185     300    0.017
     0       0        0       0    0
     0       0        0
   1.0       2        0
     0       0        0       0
     0       0        0       0
     0       0        0
 400.0       0        0
   0.0       0        0
  1.00       0        0
  0.00       0        0
     0       0
     0       0
     0       0        0       0
```

Sample environmental data file [MIAMI.DAT] used in Examples 11 and 12.

4825.00	299.610	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4826.00	299.330	0	0	0	0.1790E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4827.00	299.240	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4828.00	299.130	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4829.00	298.830	0	0	0	0.1790E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4830.00	298.920	0	0	0	0.1810E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4831.00	299.720	0	0	0	0.1840E-01	0	0	0.1594E+03	0	0	0	0	0	0	0	0	0	0	0	0
4832.00	301.710	0	0	0	0.1830E-01	0	0	0.3613E+03	0	0	0	0	0	0	0	0	0	0	0	0
4833.00	302.640	0	0	0	0.1810E-01	0	0	0.6032E+03	0	0	0	0	0	0	0	0	0	0	0	0
4834.00	303.890	0	0	0	0.1780E-01	0	0	0.8206E+03	0	0	0	0	0	0	0	0	0	0	0	0
4835.00	304.950	0	0	0	0.1780E-01	0	0	0.9409E+03	0	0	0	0	0	0	0	0	0	0	0	0
4836.00	305.370	0	0	0	0.1800E-01	0	0	0.1008E+04	0	0	0	0	0	0	0	0	0	0	0	0
4837.00	305.610	0	0	0	0.1790E-01	0	0	0.9551E+03	0	0	0	0	0	0	0	0	0	0	0	0
4838.00	306.280	0	0	0	0.1780E-01	0	0	0.8382E+03	0	0	0	0	0	0	0	0	0	0	0	0
4839.00	305.740	0	0	0	0.1740E-01	0	0	0.6341E+03	0	0	0	0	0	0	0	0	0	0	0	0
4840.00	304.220	0	0	0	0.1760E-01	0	0	0.5223E+03	0	0	0	0	0	0	0	0	0	0	0	0
4841.00	303.240	0	0	0	0.1760E-01	0	0	0.3474E+03	0	0	0	0	0	0	0	0	0	0	0	0
4842.00	302.980	0	0	0	0.1750E-01	0	0	0.2214E+03	0	0	0	0	0	0	0	0	0	0	0	0
4843.00	302.240	0	0	0	0.1770E-01	0	0	0.7560E+02	0	0	0	0	0	0	0	0	0	0	0	0
4844.00	301.240	0	0	0	0.1770E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4845.00	300.490	0	0	0	0.1770E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4846.00	300.300	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4847.00	300.000	0	0	0	0.1780E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4848.00	299.640	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0
4849.00	299.610	0	0	0	0.1800E-01	0	0	0.0000E+00	0	0	0	0	0	0	0	0	0	0	0	0

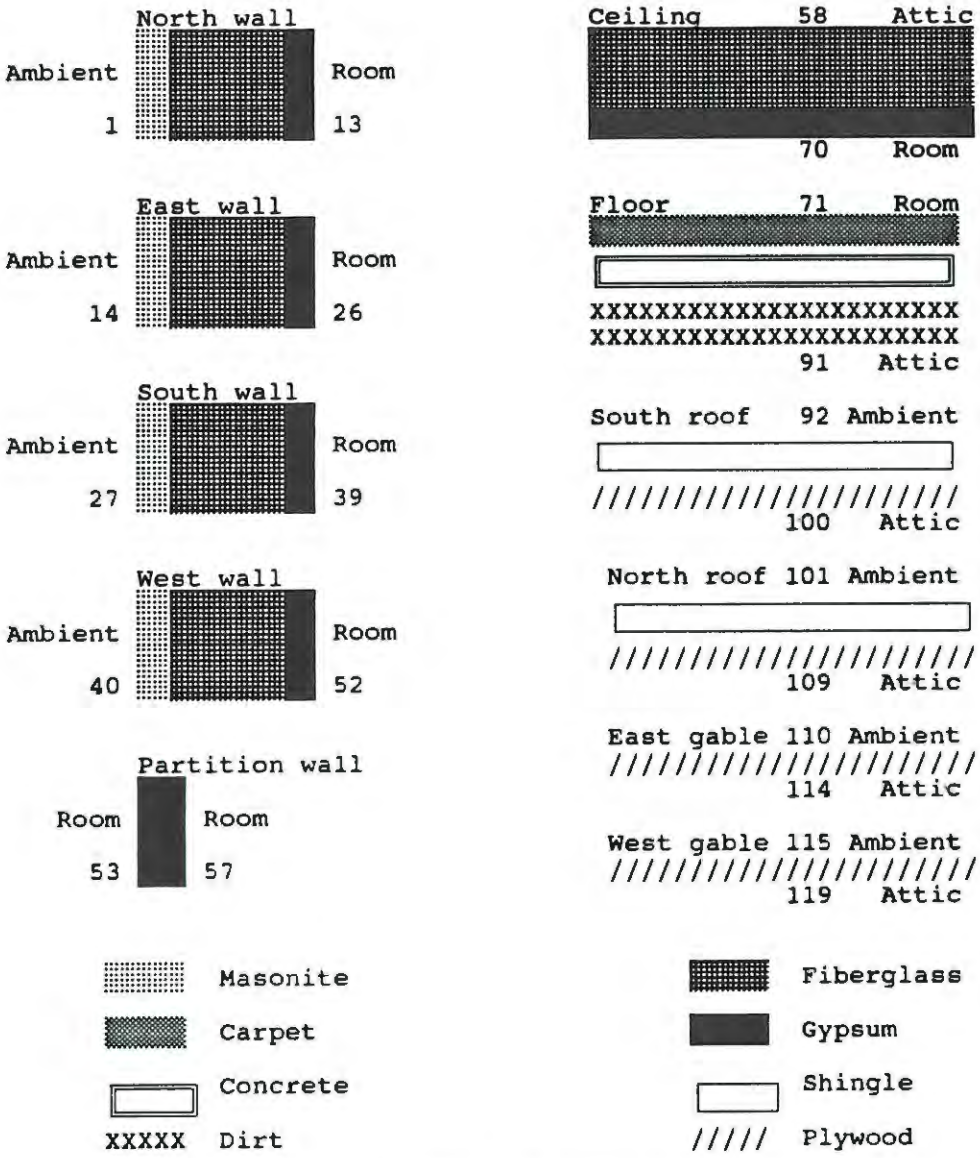


Figure 6-11.1 Wall Configuration used in Examples 11 and 12.

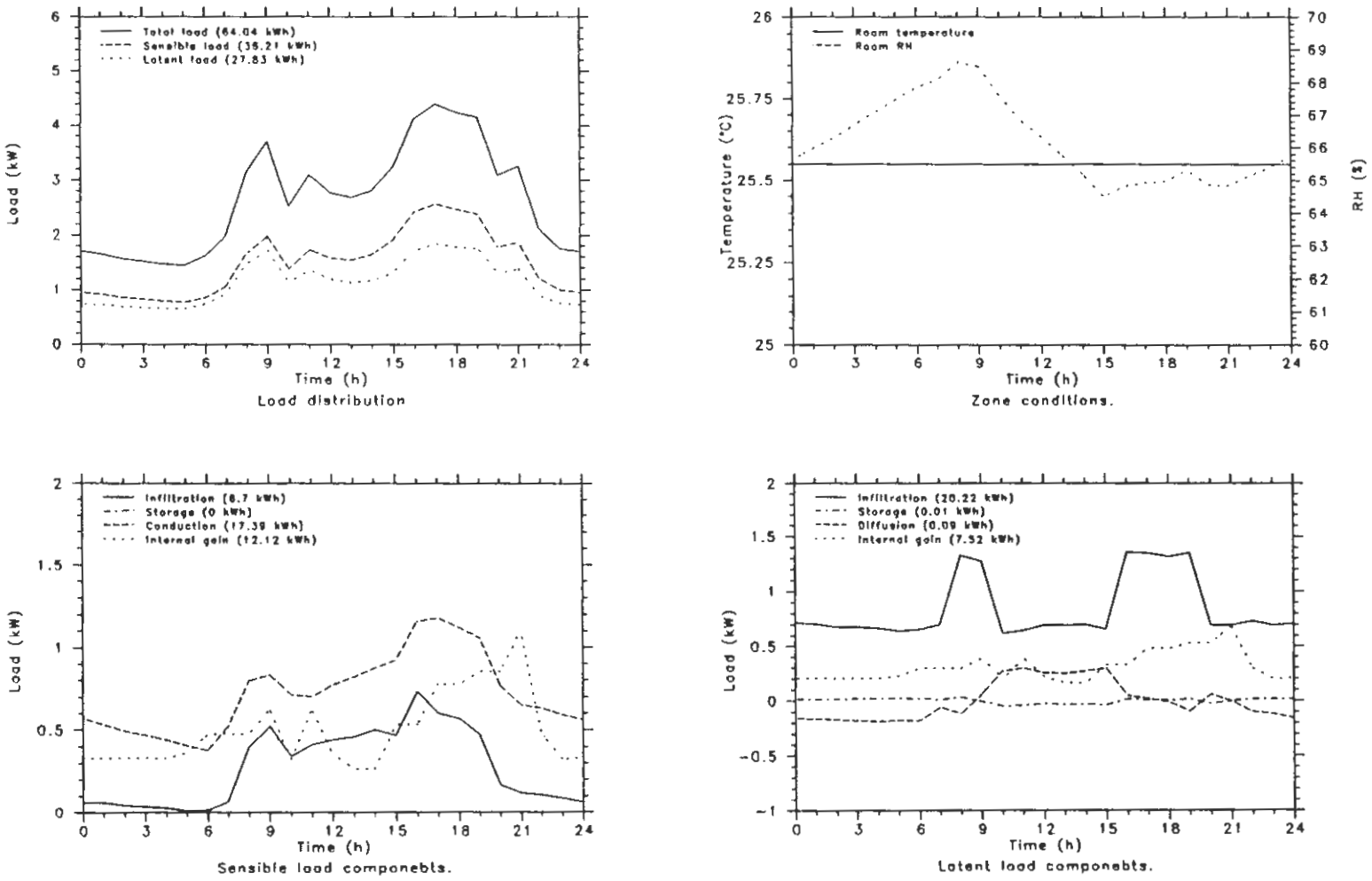


Figure 6-11.2 Zone conditions and associated loads using EMPD model.

6.12 COMBINED HEAT AND MASS TRANSFER IN BUILDING USING EVACON

In this example, the same building with identical inputs defined in Example 12 is simulated using the **EVA**poration and **CON**densation (EVACON) theory. In this simulation the temperature and moisture distribution in the walls are calculated using the distributed heat and moisture transfer equations. Note that detailed material property data are supplied in the data file for both heat and moisture transfer equations. Figure 6-12 shows the result of this simulation.

```
EXAMPLE 12. COMBINED HEAT AND MASS TRANSFER IN BUILDINGS USING EVACON.
   119    27     8     4     2     4
     1     0     0   1.0   240
     1     0   200
   1.0     0     5     0
     0     0
     2    10    13
    10   300   0.7   0.1   1.0
    13 0.014   0.7   0.1   1.0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0     0
     4    19    50   510   513
     0
```

```
ZONE12.DAT
NODE GENERATION
     1    1     5   1   0.00000   0.0   0.0   0.01111   0.0   0.0
     5    1     9   1   0.01111   0.0   0.0   0.09366   0.0   0.0
     9    1    13   1   0.09366   0.0   0.0   0.10636   0.0   0.0
    14    1    18   1   0.00000   0.0   0.0   0.01111   0.0   0.0
    18    1    22   1   0.01111   0.0   0.0   0.09366   0.0   0.0
    22    1    26   1   0.09366   0.0   0.0   0.10636   0.0   0.0
    27    1    31   1   0.00000   0.0   0.0   0.01111   0.0   0.0
    31    1    35   1   0.01111   0.0   0.0   0.09366   0.0   0.0
    35    1    39   1   0.09366   0.0   0.0   0.10636   0.0   0.0
    40    1    44   1   0.00000   0.0   0.0   0.01111   0.0   0.0
    44    1    48   1   0.01111   0.0   0.0   0.09366   0.0   0.0
    48    1    52   1   0.09366   0.0   0.0   0.10636   0.0   0.0
    53    1    57   1   0.00000   0.0   0.0   0.02540   0.0   0.0
    58    1    66   1   0.00000   0.0   0.0   0.14859   0.0   0.0
    66    1    70   1   0.14859   0.0   0.0   0.16129   0.0   0.0
    71    1    75   1   0.00000   0.0   0.0   0.01270   0.0   0.0
    75    1    83   1   0.01270   0.0   0.0   0.11430   0.0   0.0
    83    1    91   1   0.11430   0.0   0.0   0.42270   0.0   0.0
    92    1    96   1   0.00000   0.0   0.0   0.02540   0.0   0.0
    96    1   100   1   0.02540   0.0   0.0   0.05080   0.0   0.0
   101    1   105   1   0.00000   0.0   0.0   0.02540   0.0   0.0
   105    1   109   1   0.02540   0.0   0.0   0.05080   0.0   0.0
   110    1   114   1   0.00000   0.0   0.0   0.02540   0.0   0.0
   115    1   119   1   0.00000   0.0   0.0   0.02540   0.0   0.0
     0    0     0   0   0.00000   0.0   0.0   0.00000   0.0   0.0
ELEMENT GENERATION
     1    0     1     1   37.160   1     1    5    2    3    4
     2    0     2     2   37.160   1     5    9    6    7    8
     3    0     3     3   37.160   1     9   13   10   11   12
     4    0     4     1   22.300   1    14   18   15   16   17
     5    0     5     2   22.300   1    18   22   19   20   21
     6    0     6     3   22.300   1    22   26   23   24   25
     7    0     7     1   37.160   1    27   31   28   29   30
     8    0     8     2   37.160   1    31   35   32   33   34
```

```
    9     0     9    3   37.160  1    35   39   36   37   38
   10     0    10    1   22.300  1    40   44   41   42   43
   11     0    11    2   22.300  1    44   48   45   46   47
   12     0    12    3   22.300  1    48   52   49   50   51
   13     0    13    3   104.00  1    53   57   54   55   56
   14     1    15    2   139.35  4    58   62   59   60   61
   16     0    16    3   139.35  1    66   70   67   68   69
   17     0    17    4   139.35  1    71   75   72   73   74
   18     1    19    5   139.35  4    75   79   76   77   78
   20     1    21    6   139.35  4    83   87   84   85   86
   22     0    22    7   80.448  1    92   96   93   94   95
   23     0    23    8   80.448  1    96  100   97   98   99
   24     0    24    7   80.448  1   101  105  102  103  104
   25     0    25    8   80.448  1   105  109  106  107  108
   26     0    26    8   12.069  1   110  114  111  112  113
   27     0    27    8   12.069  1   115  119  116  117  118
    0     0     0    0      0    0     0    0    0    0    0
MATERIAL PROPERTY SPECIFICATION
<1> MASONITE
  0.10560  800.0000  800  1299  0.90000  0.7500  0.0000  0.0000  0.0000  0.0000
  1.26E-7  9.13E-13  0.4  6.39  4.95E-3  0.1840  0.5940  0.1119  6.7840  2.4E+6
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<2> FIBERGLASS INSULATION
  0.04600  65.00000   65   712  0.93000  0.0000  0.0000  0.0000  0.0000  0.0000
  2.35E-5  2.345E-5  0.9  .273  2.12E-4  5.782E-3 2.307  0.00384 11.325  2.4E+6
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<3> GYPSUM DRYWALL
  0.21600  720.0000  720  1340  0.90000  0.4000  0.0000  0.0000  0.0000  0.0000
  3.79E-6  2.74E-11  .72 1.626  1.26E-3  0.0725  0.3970  7.77E-3 11.706  2.4E+6
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<4> CARPET
  0.05900  250.0000  250  1520  0.90000  0.4000  0.0000  0.0000  0.0000  0.0000
  2.35E-5  1.70E-10  .85  .291  2.26E-4  8.44E-3 9.3880  6.31E-3 1.3590  2.4E+6
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<5> CONCRETE
  0.13000  2370.000 2370   880  0.90000  0.0000  0.0000  0.0000  0.0000  0.0000
  6.49E-7  4.67E-12    0  .476  3.69E-4  0.0181  0.4519  0.0262  10.836  2.4E+6
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0     0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
```

```
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<6> DIRT
  0.86550  1600.000 1600    838  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<7> SHINGLE
  1.73060  1922.000 1922   1004  0.90000  0.7500  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
<8> PLYWOOD
  0.01200  600.0000  600   1215  0.75000  0.7500  0.0000  0.0000  0.0000  0.0000
  3.54E-7  2.56E-13  0.4 6.391  4.96E-3  0.1840  0.5940  0.1119  6.7849  2.4E+6
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
  0.00000  0.000000    0      0  0.00000  0.0000  0.0000  0.0000  0.0000  0.0000
BOUNDARY CONDITION SET VALUE SPECIFICATION
BC-1 heat transfer horizontally to zone
    8.289     0   0    0    0    0    0    0    0    0
    7.08E-3   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
BC-2 heat transfer upward to zone
    9.256     0   0    0    0    0    0    0    0    0
    7.08E-3   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
BC-3 heat transfer downward to zone
    2.256     0   0    0    0    0    0    0    0    0
    7.08E-3   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
BC-4 heat transfer to ambient
     22.916   0   0    0    0    0    0    0    0    0
    7.08E-3   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
          0   0   0    0    0    0    0    0    0    0
PRESCRIBED VALUE SPECIFICATION
   299.04
   0.014
BOUNDARY CONDITION FLAG GENERATION
      1      0      1     -4    -4
     13      0     13     -1    -1
     14      0     14     -4    -4
```

```
     26     0    26    -1    -1
     27     0    27    -4    -4
     39     0    39    -1    -1
     40     0    40    -4    -4
     52     0    52    -1    -1
     53     0    53    -1    -1
     57     0    57    -1    -1
     58     0    58    -2    -2
     70     0    70    -3    -3
     71     0    71    -2    -2
     91     0    91    +1    +2
     92     0    92    -4    -4
    100     0   100    -3    -3
    101     0   101    -4    -4
    109     0   109    -3    -3
    110     0   110    -4    -4
    114     0   114    -1    -1
    115     0   115    -4    -4
    119     0   119    -1    -1
      0     0     0     0     0
INTER-ELEMENT RADIATION SURFACE GENERATION
      0     0     0     0
POINT SOURCE
      0
```

```
EXAMPLE 12. BUILDING DATA FOR "EVACON" EXAMPLE
    2      3      22     2     1     0
    2      2       1     2
  201     24     205    24   1.0
 1.18   1007   2.4E6     0     0     0     0     0     0     0
7.0E3      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
    0      0       0     0     0     0     0     0     0     0
  +41    +42     +43   -34   -35   -36   -37   -38   -39   -40
SCHEDULES
INFILTRATION IN LIVING ZONE
 0.60  0.60  0.60  0.60  0.60  0.60  0.60  1.20  1.20  0.60  0.60  0.60
 0.60  0.60  0.60  1.20  1.20  1.20  1.20  0.60  0.60  0.60  0.60  0.60
INFILTRATION IN ATTIC
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
GAIN
 0.30  0.30  0.30  0.30  0.33  0.43  0.43  0.43  0.56  0.29  0.56  0.32
 0.24  0.24  0.48  0.48  0.70  0.70  0.77  0.77  1.00  0.43  0.29  0.30
ENVIRONMENTAL DATA
 55   25.8    80.25   0.2    0    3
MIAMI.DAT
BOUNDARY CONDITION MODIFICATION
   1   -1  180.0    90.0    37.16   0.000
  13    1  180.0    90.0    37.16   0.004
  14   -1  -90.0    90.0    22.30   0.000
  26    1  -90.0    90.0    22.30   0.004
  27   -1    0.0    90.0    37.16   0.000
  39    1    0.0    90.0    37.16   0.004
  40   -1   90.0    90.0    22.30   0.000
  52    1   90.0    90.0    22.30   0.004
  53    1    0.0    90.0   104.00   0.004
  57    1    0.0    90.0   104.00   0.004
  58    2    0.0     0.0   139.35   0.000
  70    1    0.0   180.0   139.35   0.004
  71    1    0.0     0.0   139.35   0.004
  91   -1    0.0     0.0   139.35   0.000
  92   -1    0.0    30.0   80.448   0.000
 100    2    0.0   150.0   80.448   0.000
 101   -1  180.0    30.0   80.448   0.000
 109    2  180.0   150.0   80.448   0.000
 110   -2  -90.0    90.0   12.069   0.000
 114    2  -90.0    90.0   12.069   0.000
 115   -2   90.0    90.0   12.069   0.000
 119    2   90.0    90.0   12.069   0.000
SYSTEM PARAMETERS
   0
ZONE DATA
 LIVING ROOM (ZONE 1)
    334   298.7  0.014
 1793.3      3      0      0    0.6171
      0      0      0
    1.0      1      0
      0      0      0      0
      0      0      0      0
      0      0      0
 298.70      0      0
 273.15      0      0
   1.00      0      0
   0.00      0      0
      0      0
      2      0
      0      0      0      0
```

```
ATTIC (ZONE 2)
   185     300    0.017
     0       0        0       0    0
     0       0        0
   1.0       2        0
     0       0        0       0
     0       0        0       0
     0       0        0
 400.0       0        0
   0.0       0        0
  1.00       0        0
  0.00       0        0
     0       0
     0       0
     0       0        0       0
```

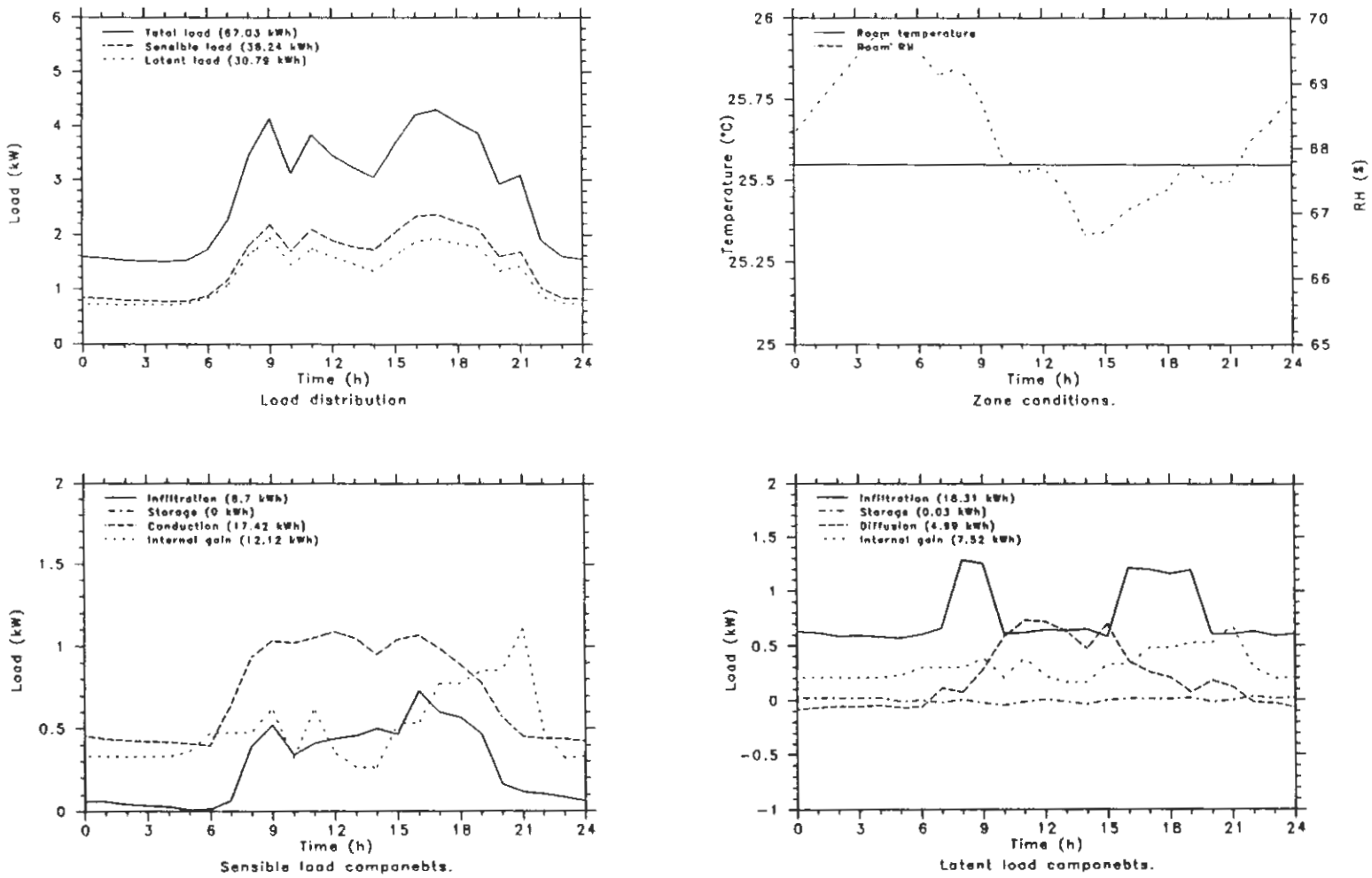


Figure 6-12 Zone conditions and associated loads using EVACON model.

APPENDIX A: OUTPUT AND INPUT DATA FILE FORMAT

This appendix provides the format and content of each input and output file used by the software. Definitions of the Fortran codes used are provided after each file.

CTLOUT OUTPUT FILE [<FL>.CTL]

```
IF (IOUT(20).EQ. 20) THEN
      OPEN (UNIT=11, NAME=CTLOUT, STATUS= 'NEW')
            WRITE (11,500) CTLOUT
            WRITE (11,500) TITLE
            WRITE (11, *) MAXITR, NEWTON
            DO I=1, NOFEQN
                  WRITE (11,*) NEQ, RLX(NEQ), ERROR(NEQ)
            END DO
      END IF
500   FORMAT (A)
```

Defintions:

CTLOUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
MAXITR	Maximum number of iterations
NEWTON	Iteration type
NOFEQN	Total number of equations solved in the simulation
NEQ	Equation number
RLX(NEQ)	Relaxation parameter for equation NEQ
ERROR(NEQ)	Error tolerance for equation NEQ

FLXOUT OUTPUT FILE [<FL>.FLX]

```
IF (IOU(21).EQ.21) THEN
                    O     P     E     N
(UNIT=12,NAME=FLXOUT,TYPE='NEW',FORM='UNFORMATTE
D)
      WRITE (12) FLXOUT
      WRITE (12) TITLE
      WRITE (12) NOFNOD, NOFELE, NOT
      WRITE (12) NOFEQN, NUMEQN(I), I=1,NOFEQN)
      WRITE (12) TINE, TSTP, TFIN
      WRITE (12) STIME, MODE
      DO NOE=1,NOFELE
            WRITE (12)CO(1),CO(2),((FX(I,J),J=1,2),I=1,4)
      END DO
END IF
```

Definitions:

FLXOUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
NOFNOD	Total number of nodes used in the simulation
NOFELE	Total number of elements used in the simulation
NOFEQN	Total number of equations solved in the simulation
NOT	Element type
NUMEQN(1)	Dimensioned variable that contains the equation number
TINT	Simulation start time (always in hours)
TSTP	Simulation time step (always in hours)
TFIN	Simulation stop time (always in hours)
STIM	Simulation time (always in hours)
MODE	Simulation mode (0 for steady-state, 1 for transient simulation)
CO(1)	X-coordinate of the element centroid
CO(2)	Y-coordinate of the element centroid
FX(1,1)	Centroid velocity in the x-coordinate
FX(1,2)	Centroid velocity in the y-coordinate
FX(2,1)	Centroid heat flux in the x-coordinate
FX(2,2)	Centroid heat flux in the y-coordinate

FX(3,1)	Centroid moisture in the x-coordinate
FX(3,2)	Centroid moisture in the y-coordinate
FX(4,1)	Centroid contaminant flux in the x-coordinate
FX(4,2)	Centroid contaminant flux in the y-coordinate

MSHOUT OUTPUT FILE [<FL>.MSH]

```
IF (IOUT(22). EQ.22) THEN
                    O     P     E     N
(UNIT=13, NAME=MSHOUT, TYPE='NEW',FORM='UNIFORMED')
      WRITE (13) MSHOUT
      WRITE (13) TITLE
      WRITE (13) NOFNOD, NOFELE, NOT
      WRITE (13) TINE, TSTP, TFIN
      DO I=1, NOFELE
            WRITE (13) (XL(NC(9)+(I-1)*NON+J, J=1, NON)
      END DO
      DO I=1, NOFELE
            WRITE (13) XL(NC(2)+I)
      END DO
      WRITE (13) STIM, MODE
      DO I=1, NOFNOD
            WRITE (13) XL (I*3-2), XL(I*3-1), XL(I*3)
      END DO
END IF
```

Definitions:

MSHOUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
NOFNOD	Total number of nodes used in the simulation
NOFELE	Total number of elements used in the simulation
NOT	Element type
TINT	Simulation start time (always in hours)
TSTP	Simulation time step (always in hours)
TFIN	Simulation stop time (always in hours)
NON	Number of nodes for the element

XL(##)	Global node number of the Jth node of the Ith element's connectivity, ##::=NC(9)+(I-1)*NON+J
STIM	Simulation time (always in hours)
MODE	Simulation mode (0 for steady-state, 1 for transient simulation)
XL(3*I-2)	X-coordinate of the Ith node
XL(3*I-1)	Y-coordinate of the Ith node
XL(3*I)	Z-coordinate of the Ith node

RESOUT OUTPUT FILE [<FL>.RES]

```
IF (IUOT(23).EQ. 23) THEN
                    O     P     E     N
(UNIT=14, NAME=RESOUT, TYPE='NEW', FORM-'UNFORMATTED')
      WRITE (14) RESOUT
      WRITE (14) TITLE
      WRITE (14) NOFNOD, NOFELE, NOT
      WRITE (14) NOFEQN+I1*4, (NUMEQN(I), I=1,NOFEQN),
            (25+I, I=1,I1*4)
      WRITE (14) TINT, TSTP, TFIN
      WRITE (14) STIM, MODE
      DO I=1,NOFNOD
      WRITE(14)(XL(NC(1350+NUMEQN(J))+I),J=1,NOFEQN
            XL(NC(1650)+I*4-4+J), J=1,I1*4)

      END DO
END IF
```

Definitions:

RESOUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
NOFNOD	Total number of nodes used in the simulation
NOFELE	Total number of elements used in the simulation
NOT	Element type
I1	Variable is equal to 1 if equations 13 and 14 are solved, otherwise it is equal to 0
NOFEQN	Total number of equations solved in the simulation
NUMEQN(I)	Dimensioned variable that contains the equation numbers

TINT	Simulation start time (always in hours)
TSTP	Simulation time step (always in hours)
TFIN	Simulation stop time (always in hours)
STIM	Simulation time (always in hours)
MODE	Simulation mode (0 for steady-state, 1 for transient simulation)
XL(##)	Nodal unknown for the Ith node of NUMEQN(J)th equation ##::=NC(1350+NUMEQN(J))+I.

VIWOUT OUTPUT FILE [<FL>.VIW]

```
IF (IOUT(24) .EQ. 24) THEN
                    O     P     E     N
(UNIT=10, NAME=VIWOUT, TYPE='NEW',
FORM='UNFORMATTED')
      WRITE (10) VIWOUT
      WRITE (10) TITLE
      WRITE (10) NOFRAD
      DO I=1,NOFRAD
            WRITE (10) NOEI, LEGI, NOD, (NBC(J),J=I,NOD), A1
            DO J=I+1,NOFRAD
                  WRITE (10) NOEJ, LEGJ, A2, F12
            END DO
      END DO
END IF
```

Definitions:

VIWOUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
NOFRAD	Total number of surfaces or legs participating in inter-element radiation
NOEI	Element number containing the emitting surface
LEGI	Emitting surface or leg number
NOD	Number of nodes constituting the emitting surface or leg
NBC(J)	Inter-element boundary condition flag assigned to each node of the emitting surface or leg
A1	Emitting surface area
NOEJ	Element number containing the absorbing surface

LEGJ	Absorbing surface or leg number
A2	Absorbing surface area
F12	Thermal radiation view factor

VOROUT OUTPUT FILE [<FL>.VOR]

```
IF (IOUT(25) .EQ. 25) THEN
                                    O     P     E     N
(UNIT=10,NAME=VOROUT,TYPE='NEW',FORM='UNFORMATTED')
       WRITE (10) VOROUT
       WRITE (10) TITLE
       WRITE (10) NDIV
       DO I=1,NOFNOD
     WRITE (10) NODE, XC, YC, ZC, NOE, R, S, NBC
       DO J=2,NDIV
         WRITE (10) NODE, XC, YC, ZC, NOE, R, S
       END DO
  END DO
END IF
```

Definitions:

VOROUT	Alphanumerical file name
TITLE	Alphanumerical problem or simulation title
NDIV	Number of fluid nodes used in the wall vorticity calculations
NODE	Global node number for the wall node where its vorticity value is calculated using the wall vorticity equation
XC	X-coordinate of the fluid node
YC	Y-coordinate of the fluid node
ZC	Z-coordinate of the fluid node
NOE	Element number which contains the fluid node
R	Local normalized coordinate of the fluid node in the r-direction
S	Local normalized coordinate of the fluid node in the s-direction
NBC	Vorticity boundary condition flag assigned to the wall node

MSHGET INPUT FILE

```
IF (MSHGET .NE. ' ') THEN
                                    O     P     E     N
(UNIT=10,NAME=MSHGET,TYPE='OLD',FORM='UNFORMATTED')
      READ (10) MSHGET
      READ (10) TITLE
      READ (10) NOFNOD, NOFELE, NOT
      READ (10) TINT, TSTP, TFIN
      DO I=1,NOFELE
            READ (10) (NN(J),J=1,NON)
      END DO
      DO I=1,NOFELE
            READ (10) MATSET(I)
      END DO
      DO I=1,NOFNOD
            READ (10) (COOR(J),J=1,3)
      END DO
      DO I=1,NOFELE
            READ (10) NOT(I), AREA(I)
      END DO
      READ (10) NOFEQM,(NUMEQM(I),I=1,NOFEQM)
      DO I=1,NOFNOD
            READ (10) (BCFLG1(J),J=1,NOFEQM)
      END DO
      DO I=1,NOFEQM
            DO J=1,NOFELE
                  READ (10) (BCFLG2(K),K=1,NOL)
            END DO
      END DO
END IF
```

Definitions:

MSHGET	File name
TITLE	Alphanumerical problem or simulation title
NOFNOD	Total number of nodes used in the simulation
NOFELE	Total number of elements used in the simulation
NOT	Element type used in the simulation
TINT	Starting time

TSTP	Simulation time step
TFIN	Final time
COOR(J)	Array that contains the x-, y- and z-coordinates of the node
NOT(I)	Array that contains each element's element type
NON	Number of nodes for the element
NN(J)	Array that contains the nodal connectivity of each element
AREA(I)	Array that contains the area or thickness of each element
NOFEQM	Number of equations
NUMEQM(I)	Array that contains the equation numbers
MATSET(I)	Array that contains the material set flags of each element
BCFLG1(J)	Array that contains the 1st kind B.C. flags for each node
BCFLG2(K)	Array that contains the 2nd and 3rd kind B.C. flags for each leg of the element
NOL	Number of legs

USEGET INPUT FILE

```
O                P                E                N
(UNIT=15,NAME=USEGET,TYPE='OLD',FORM='UNFORMATTED')
READ (15) USEGET
READ (15) TITLE
READ (15) NOFNOD, NOFELE, NOT
READ (15) NOFEQN, (NUMEQN(I), I=1,NOFEQN)
READ (15) TINT, TSTP, TFIN
READ (15) STIM, MODE
DO I=1,NOFNOD
  READ (15) (XL(NC(1350+NUMEQN(J))+I), J=1,NOFEQN)
     END DO
```

The format of this input file is identical to the format of RESOUT file.

INIGET INPUT FILE

```
O                P                E                N
(UNIT=10,NAME=INIGET,TYPE='OLD',FORM='UNFORMATTED')
READ (10) USEGET
READ (10) TITLE
READ (10) NOFNOD, NOFELE, NOT
READ (10) NOFEQN, (NUMEQN(I), I=1,NOFEQN)
READ (10) TINT, TSTP, TFIN
READ (10) STIM, MODE
DO I=1,NOFNOD
      READ (10) (XL(NC(1350+NUMEQN(J))+1), J=1,NOFEQN)
END DO
```

The format of this input file is identical to the format of RESOUT file.

VIWGET INPUT FILE

```
IF (VIWGET .NE. ' ') THEN
                                   O    P    E    N
(UNIT=10,NAME=VIWGET,TYPE='OLD',FORM='UNFORMATTED')
      READ (10) VIWOUT
      READ (10) TITLE
      READ (10) NOFRAD
      DO I=1,NOFRAD
            READ (10) NOEI, LEGI, NOD, (NBC(J), J=1,NOD), A1
          DO J=I+1,NOFRAD
            READ (10) NOEJ, LEGJ, A2, F12
            END DO
      END DO
END IF
```

The format of this input file is identical to the format of VIWOUT file.

VORGET INPUT FILE

```
IF (VORGET .NE. ' ') THEN
                                    O     P     E     N
(UNIT=10,NAME=VORGET,TYPE='OLD',FORM='UNFORMATTED')
      READ (10) VOROUT
      READ (10) TITLE
      READ (10) NDIV
      DO I=1,NOFNOD
            READ (10) NODE, XC, YC, ZC, NOE, R, S, NBC
            DO J=2,NDIV
                  READ (10) NODE, XC, YC, ZC, NOE, R, S
            END DO
      END DO
END IF
```

The format of this input file is identical to the format of VOROUT file.

APPENDIX B: INPUT SUMMARY

This appendix provides the format and content of input summaries of each file. Each line indicates what the program will read.

INPUT SUMMARY FOR THE MAIN PROGRAM

Master Control

```
LINE 01 ::=      TITLE
LINE 02 ::=      NOFNOD, NOFELE, NOFMAT, NOFBCO, NOFPRS,
                 NETYPE
LINE 03 ::=      MODE, ILMP, TINT, TSTP, TFIN
LINE 04 ::=      NDOF, NEWTON, MAXITR
LINE 05 ::=      SCALE, NDISTR, NOFGAU, NVORTY
LINE 06 ::=      MODSTR
LINE 07 ::=      NOFEQN, (NUMEQN(I), I=1,NOFEQN)
                 DO I=1,NOFEQN
LINE 08 ::=      NEQ, VO, RLX, ERROR, THETA
            END DO
LINE 09 ::=      CON(I), I=01,10
LINE 10 ::=      CON(I), I=11,20
LINE 11 ::=      CON(I), I=21,30
LINE 12 ::=      CON(I), I=31,40
LINE 13 ::=      CON(I), I=41,50
LINE 14 ::=      VRG(I), I=01,10
LINE 15 ::=      VRG(I), I=11,20
LINE 16 ::=      VRG(I), I=21,30
LINE 17 ::=      VRG(I), I=31,40
LINE 18 ::=      VRG(I), I=41,50
LINE 19 ::=      VRL(I), I=01,10
LINE 20 ::=      VRL(I), I=11,20
LINE 21 ::=      VRL(I), I=21,30
LINE 22 ::=      VRL(I), I=31,40
LINE 23 ::=      VRL(I), I=41,50
LINE 24 ::=      NOFOUT, (O(I), I=1,NOFOUT)
```

```
LINE 25 ::=        NOFPRT
           DO I=1,NOFPRT
LINE 26 ::=        PTS, PDT, PTF
           END DO
LINE 27 ::=        VORGET
LINE 28 ::=        VIWGET
LINE 29 ::=        INIGET
LINE 30 ::=        USEGET
LINE 31 ::=        MSHGET
LINE 32 ::=        ZONGET
```

Node Generation

```
LINE 01 ::=        SUBT
LINE 02 ::=        NS, NI, NF, SP, XS, YS, ZS, XF, YF, ZF
                   .
                   .
                   .
```

Element Generation

```
LINE 01 ::=        SUBT
LINE 02 ::=        NS, NI, NF, MS, AR, NA, (NN(I), I=1,NON)
                   .
                   .
                   .
```

Material Property Specification

```
LINE 01 ::=        SUBT
           DO I=1,NOFMAT
LINE 02 ::=        SUBT
LINE 03 ::=        (PRO(J), J=001,010)
LINE 04 ::=        (PRO(J), J=011,020)
LINE 05 ::=        (PRO(J), J=021,030)
LINE 06 ::=        (PRO(J), J=031,040)
LINE 07 ::=        (PRO(J), J=041,050)
LINE 08 ::=        (PRO(J), J=051,060)
LINE 09 ::=        (PRO(J), J=061,070)
LINE 10 ::=        (PRO(J), J=071,080)
LINE 11 ::=        (PRO(J), J=081,090)
LINE 12 ::=        (PRO(J), J=091,100)
           END DO
```

Boundary Condition Set Value Specification

```
LINE 01 ::=        SUBT
           DO I=1,NOFBCO
LINE 02 ::=        SUBT
LINE 03 ::=        (BCO(J), J=001,010)
LINE 04 ::=        (BCO(J), J=011,020)
LINE 05 ::=        (BCO(J), J=021,030)
LINE 06 ::=        (BCO(J), J=031,040)
           END DO
```

Prescribed Value Specification

```
LINE 01 ::=        SUBT
           DO I=1,NOFPRS
LINE 02 ::=        PV(I)
           END DO
```

Boundary Condition Flag Generation

```
LINE 01 ::=        SUBT
LINE 02 ::=        NS, NI, NF, (NBC(NUMEQN(I)), I=1,NOFEQN)
                   .
                   .
                   .
```

Wall Vorticity Distance Specification

```
LINE 01 ::=        SUBT
LINE 02 ::=        NS, NI, NF, DIST
                   .
                   .
                   .
```

Inter-Element Radiation Surface Generation

```
LINE 01 ::=      SUBT
LINE 02 ::=      NS, NI, NF, NBC
                 .
                 .
                 .
```

Point Source Specification

```
LINE 01 ::=      SUBT
LINE 02 ::=      NOFSOR
           DO I=1,NOFSOR
LINE 03 ::=      NEQ, XCOR, YCOR, ZCOR, VALUE
           END DO
```

INPUT SUMMARY FOR THE BUILDINGS PROGRAM

Master Control

```
LINE 01 ::=     TITLE
LINE 02 ::=     NOFZON, NOFSCH, NOFSUR, MODZON
LINE 03 ::=     SDAY, SHOUR, EDAY, EHOUR, TSTP
LINE 04 ::      (CONST(I), I=01,10)
LINE 05 ::      (CONST(I), I=11,20)
LINE 06 ::      (CONST(I), I=21,30)
LINE 07 ::      (CONST(I), I=31,40)
LINE 08 ::      (CONST(I), I=41,50)
LINE 09 ::      (O(I), I=1,10)
```

Schedule Specification

```
LINE 01 ::=         SUBT
          DO I=1,NOFSCH
LINE 02 ::=         SUBT
LINE 03 ::=         (S(I), I=01,12)
LINE 04 ::=         (S(I), I=13,24)
          END DO
```

Environmental Data Specification

```
LINE 01 ::=     SUBT
LINE 02 ::=     STDMRD, ZLATIT, ZLONGT, GRDREF, SOLFLG,
                JSLCOR
LINE 03 ::=     ENVGET
```

Boundary Condition Modification

```
LINE 01 ::=        SUBT
           DO I=1,NOFSUR
LINE 02 ::=        NODE, NBCFLG, AZIMUT, TILT, AREA, EMPD
           END DO
```

System Parameters

```
LINE 01 ::=        SUBT
LINE 02 ::=        MECHNO
```

Zone Data

```
LINE 01 ::=        SUBT
           DO I=1,NOFZON
LINE 02 ::=        SUBT
LINE 03 ::=        VOLUME, TRMOLD, WRMOLD
LINE 04 ::=        CAPEQP, NSCEQP, CTREQP, RFREQP, SFREQP
LINE 05 ::=        CAPFAN, NSCFAN, CTRFAN
LINE 06 ::=        CAPINF, NSCINF, CTRINF
LINE 07 ::=        CAPLGT, NSCLGT, CTRLGT, RFRLGT
LINE 08 ::=        CAPPEO, NSCPEO, CTRPEO, SFRPEO
LINE 09 ::=        CAPVEN, NSCVEN, CTRVEN
LINE 10 ::=        SETTMX, NSCTMX, CTRTMX
LINE 11 ::=        SETTMN, NSCTMN, CTRTMN
LINE 12 ::=        SETWMX, NSCWMX, CTRWMX
LINE 13 ::=        SETWMN, NSCWMN, CTRWMN
LINE 14 ::=        DEADBT, DEADBW
LINE 15 ::=        COLSNO, HETSNO
LINE 16 ::=        RADFRC, QMASSS, QMASSL
           END DO
```

INPUT SUMMARY FOR THE MESH GENERATION PROGRAM

Master Control

LINE 01 ::= TITLE
LINE 02 ::= NOSNOD, NOSELE, DOOPTI
LINE 03 ::= NOFEQM, (NUMEQM(I), I=1,NOFEQM)

Super Element Nodal Coordinate Generation

LINE 01 ::= SUBT
LINE 02 ::= NODE, XCOR, YCOR, ZCOR

.
.
.

Super Element Node Generation

LINE 01 ::= SUBT
LINE 02 ::= NOE, NOTSUP, (NN(I),I=1,NONDAT(NOTSUP))
LINE 03 ::= NONX, NONY, NONZ, SPFX, SPFY, SPFZ, NTYPE, MATSET, AREA

.
.
.

Prescribed Boundary Condition Generation

```
LINE 01 ::=     SUBT
LINE 02 ::=     NOF, NA, NON, (NN(I),I=1,NON), (NPV(I),
                I=1,NOFEQM)
                .
                .
                .
```

2nd And 3rd Kind Boundary Condition Generation

```
LINE 01 ::=     SUBT
LINE 02 ::=     NOF, NA, NON, (NN(I),I=1,NON), (NBC(I),
                I=1,NOFEQM)
                .
                .
                .
```

GLOSSARY

Algebraic Finite Element Statement (AFES):

The statement obtained after performing the Galerkin formulation to a differential equation

Anisotropic:

A characteristic of a material that exhibits spatial variation in properties

Backus-Naur Form (BNF):

A symbolic language

Boundary Condition Set:

The parameters that completely define the forcing function at a boundary

Boundary Condition Flag:

A number that identifies from a list of forcing functions, the particular one applicable to a boundary

Buoyancy :

The result of tbe combined presence of a fluid density gradient and body force that is proportional to density

Capacitance Matrix:

A matrix that determines the coefficients of the nodal unknowns in the time domain

Capillary:

The capability to rise or depress a liquid in a small passage and is the result of surface or interfacial forces

Cartesian Co-ordinate:

The scheme for locating points in a Eudidean space by means of numerical quantities specified with respect to the frame with mutually perpendicular three axes

Centroid:

The points positioned identically with the centers of gravity of corresponding homogeneous thin plates or thin wires

Common Blocks:

The process in which one or more contiguous areas share the same data among two or more processes

Compressible Flow:

The flow in which the fluid density varies

Confined Aquifer:

A confined subsurface zone that yield economically important amounts of water to wells

Contaminant Flux:

The magnitude of continuous moving on or passing by the surface of contaminant species

Convergence:

A limit that is approached as the number of terms increase without limit

Crank-Nicolson Central Difference Scheme:

A procedure for solving a system of algebraic equations

Diffusivity:

A measure of the rate of diffusion of a substance

Dimensionless:

A combination of dimensional or dimensionless quantities that posses zero dimensions

Discretize:

The process of subdividing an area of interest

Double Precision:

Dynamic Viscosity:

The ration of the shearing stress to the shear of the motion

Elemental Capacitance:

The capacitance matrix of each element

Emissivity:

The ratio of the power per unit area radiated by a surface to that radiated by a black body at the same temperature

Equilibrium Moisture Content Curve:

A curve relating the equilibrium moisture content of a material to the relative humidity of the air it is in equilibrium with

Evaporation/Condensation Theory:

A set of spatially distributed equations for modeling detailed combined heat and moisture transport in solids

Force Vector:

A matrix that determines the forcing function in AFES

Galerkin Finite Element Method:

A method used to formulate a constrained minimization problem

Gauss-Legendre Quadrature:

A process of performing numerical integration of a problem

Green-Gauss Theorem:

A term used variously in mathematical literature to denote the divergence theory

Hydraulic Head:

The potential of a fluid described with reference to height

Incompressible Flow:

The flow in which the fluid density does not vary

Iterative Procedure:

A procedure to solve a system of equations by starting with an initial guess and approaching the true solutions

Laminar Flow:

A type of fluid flow in which the movement of the fluid particulars are well defined

Library Equations:

The equations built into FSEC 3.0

Liquidus Temperature:

The temperature at which a material is completely converted into liquid

Luikov's Theory:

A theory that describes the movement of moisture in solids

Lumped Domains:

A collection of matter in which no spatial variation of a field variable is assumed

Material Sets:

A number that identifies the nature of a material

Node:

A point of interest in a domain where the solution is sought

Output Option Flags:

A number that identifies to the program the parameters are to be printed

Solidus Temperature:

The temperature at which a material completely solidifies when cooled from a liquid state

Spatial Discretization:

A subdivision of an area of interest in space

Spatially Invariant:

A parameter that does not vary with respect to space

Steady-State:

A phenomenon that does not change with time

Stiffness Matrices:

A coefficient matrix of the AFES connected with the field variable

Temporal Discretization:

A division in time

Tortuosity:

A property that describes how tortous the path for moisture transport in a solid is compared to air

Transient Problem:

A problem in which the parameter changes with time

A

Algebraic Finite Element Statement 4-10
Alpha Parameter 3-33
Ambient Boundary Conditions for Solid Domains 5-4
Ambient Conditions 3-13
Ambient Dry Bulb Temperature 3-11, 3-31
Ambient Humidity Ratio 3-12
Azimuth Angle 3-13

B

Backus-Naur Form 4-12, 4-13
Backward Difference Scheme 2-15
Balanced Infiltration Rate 3-33
Boes et al. Correlation 3-10
Boundary Condition Flag 3-13
Boundary Condition Flag Generation 2-55, 2-56
Boundary Condition Modification 3-13
Boundary Condition Value Specification 2-51, 2-55
Building Infiltration Rate 3-23
Building Science Applications 1-4

C

Central Difference Scheme 2-15
Common Blocks 3-25
Computational Processor Segment 1-5
Confined Aquifer 5-26, 5-27, 5-28
Conservation of Mass 5-5
Conservation of Momentum 5-5
Constant Array 3-5
Constant Capacity Mechanical System 3-26
Contaminant Diffusivity 5-19
Contaminant Distribution Equations 5-18, 5-19
Cooling System Number 3-22
Crank-Nicolson 2-15

D

Density of Air 3-25
Dissipation Function 5-11
Domain and Surface Definitions 5-3
Dynamic Viscosity 5-6

E

Element Generation 2-36, 2-38 2-41, 2-42, 2-43
Energy Equations 3-2
Environmental Data File Format 3-12
Environmental Data Specification 3-10, 3-25, 3-30
Equilibrium Moisture Content Curve 5-13
Equipment Control Number 3-18
Erb's Correlation 3-10
Evaporation/Condensation Theory 5-11, 5-15, 5-16

F

Finite Element Mesh 3-13
Fluid Flow Equations 5-5, 5-6

G

Galerkin 2-15
Galerkin Finite Element Method 4-17
Gamma Parameter 3-33
Gauss Points 2-5, 2-6, 2-11
Gauss-Legendre 4-12
Global Modifications 4-1, 4-6
Green-Gauss Theorem 4-8
Ground Reflectance 3-10

H

Hardware Requirements 1-1, 1-8
Heat and Mass Transfer Simulations 5-12
Heat and Moisture Transfer Equations 5-11, 5-15

H

Heat of Vaporization 3-25
Heat Removal Rate 3-25
Heat Simulation Mode 3-2
Heat Transfer Surfaces 3-2, 3-13, 3-14
Heating System Number 3-22
Holland's Correlation 3-10
Horizontal Solar Radiation 3-11
Humidistat Dead Band 3-22
Humidistat Lower Set Point 3-21, 3-28
Humidistat Lower set Point Control Number 3-21
Humidistat Lower Set Point Schedule 3-21
Humidistat Upper Set Point 3-28
Humidistat Upper Set Point Control Number 3-21
Humidistat Upper Set Point Schedule 3-21

I

Infiltration Control Number 3-19
Infiltration Mass Flow Rate 3-28
Infiltrate Rate 3-19
Infiltration Schedule Number 3-19
Inflow Boundary Conditions 5-4
Input Directions 2-1
Input Parameters 3-25
Inside Surface Temperatures 3-8
Inside Surface Vapor Densities 3-8
Installation and Execution Procedures 1-1, 1-8
Inter-Element Radiation Surface Generation 2-59
Interface Boundary Conditions 5-4
Internal Heat Generation 3-18
Internal Load Generation 3-19, 3-20, 3-28

J

Jocobian Matrix 2-10, 2-21
Jordan's correlation 3-10

L

Laminar Flow 5-6, 5-9, 5-13, 5-19
Latent Heat Removal 3-27
Library Equations 1-2, 2-17, 2-26 5-2, 5-12, 5-18
Lighting Control Number 3-19
Lighting Schedule Number 3-19
Liu's Correlation 3-10
Local Modifications 4-1, 4-6, 4-7
Luikov's Theory 2-53, 5-16, 5-17
Lumped and Distributed Equation Interface 5-4
Lumped Capacitance Matrix 2-8, 2-9, 2-16
Lumped Moisture Equations 3-2

M

Mass Conservation Equation 5-24, 5-25
Mass Diffusivity 5-13
Master Control 2-4, 2-29, 3-2
Material Property Specification 2-43
Material Sets 2-4
Moisture Capacitance 3-24
Moisture Diffusivity 3-24
Moisture Equations 3-2
Moisture Removal Rate 3-25
Moisture Simulation Mode 3-2
Moisture Transfer Surfaces 3-2, 3-13, 3-14
Molecular Diffusivity 5-14

N

Newton-Raphson Iteration 2-10
Node Generation 2-34, 2-38 2-40, 2-41
Node Number 3-13

O

Orgil's Correlation 3-10
Outflow Boundary Conditions 5-4

O

Optput Option Flags 3-8
Outside Surface Temperatures 3-8
Outside Surface Vapor Densities 3-8

P

Penalty Finite Element Method 5-6
People Control Number 3-20
People Schedule number 3-20
Point Source Specification 2-62
Positive Integer Number 3-8
Prescribed Value Specification 2-55

Q

Quasi Newton-Raphson 2-10
Quick Moisture Mass Factor 3-24
Quick Thermal Mass Factor 3-24

R

Rain Flag 3-12
Reynolds Number 2-21

S

Schedule Specification 3-9
Sensible Heat Fraction 3-26
Simulation of Field Variable Dependant Material Property 4-7
Simulation of Time and Space Variant Variable 4-7
Simulation of Time Dependant Boundary Condition 4-6
Simulation of Variable time Step 4-6
Simulation Time 3-1
Sinusoidal Convective Fluid Side Temperature 4-6
Solar Diffuse 3-10
Solar Radiation 3-24
Solid-Gas Interface Boundary Conditions 5-4
Spatially Distributed 1-5
Spatially Lumped 1-4, 1-5
Specific Heat of Air 3-25
Stack Driven Infiltration Rate 3-33
Steady-state Problems 4-9
Stefan-Boltzmann Constant 2-20
Stream Function Equations 5-7, 5-8, 5-9
System Parameters 3-16
Systeme Internationale 3-1

T

Thermal Capacitance 3-24
Thermal Conductivity 5-13
Thermostat Dead Band 3-22
Thermostat Lower Set Point 3-21
Thermostat Lower Set Point Control Number 3-21, 3-28
Thermostat Lower Set Point Schedule 3-21, 3-28
Thermostat Set Point 3-23
Thermostat Upper Set Point 3-20
Thermostat Upper Set Point Control Number 3-20
Thermostat Upper set Point Schedule 3-20
Tilt Angle 3-14
Time correction Flag 3-10
Total Correlation Flag 3-10
Total Infiltration Flag 3-33
Transient Problems 4-9
Turbulence Equation κ-ϵ Model 5-20, 5-21
Turbulent Eddy Viscosity 5-20
Turbulent Flow 5-6, 5-9 5-13, 5-19

U

Unbalanced Infiltration Rate 3-33
Unconfined Aquifer 5-29
Undistorted for Node Rectangular 4-7
User Defined Equations 4-1, 4-8 4-16, 4-19
User Defined Programs 1-7, 4-1
User defined Routines 4-1
User Defined Routines Buildings Program 3-28, 3-29 3-31, 3-34

V

Vapor Diffusivity 3-15, 5-14
Ventilation Control Number 3-20
Ventilation Control Temperature 3-31
Ventilation Mass Flow Rate 3-28, 3-31
Ventilation Rate 3-20
Ventilation Schedule Number 3-20
Vertical Ellipses 2-1
Vorticity Equations 5-7, 5-8, 5-9

W

Wall Vorticity Distance Specification 2-58
Wall-Vorticity Boundary Conditions 5-10
Weather Tape 3-11
Wind Driven Infiltration Rate 3-33

Z

Zone Data 3-17
Zone Humidity Ratio 3-17, 3-23, 3-25, 3-30
Zone Temperature 3-17, 3-23, 3-25, 3-30
Zone Thermal Loads 3-27
Zone Volume 3-17, 3-30

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