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System Interactions in Forced-air Heating and Cooling Systems, Part I: Equipment Efficiency Factors

Lixing Gu, Ph.D., P.E., Muthusamy V. Swami, Ph.D., and Philip W. Fairey
Florida Solar Energy Center (FSEC)

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INTRODUCTION

ASHRAE Standard 152P (ASHRAE 2001) combines field measurements with calculations to quantify the efficiency of residential thermal distribution systems. To do this, it considers not only direct energy losses from the duct system, via conduction and air leakage, but also indirect effects that the duct system may have on the efficiency of the equipment or on the heating/cooling load. Although Standard 152P includes non-ducted thermal distribution systems in its scope, the subject matter of this paper is, however, restricted to ducted systems.

Originally, the standard used a simple equation, derived from first principles, to characterize thermal distribution efficiency:

ndist = DE * Fequip * Fload (1)

where ndist is distribution efficiency, defined as the ratio of input energy required to meet the heating/cooling load if the duct system were “perfect” to the input energy needed by the system under evaluation. (A perfect duct system is defined as one that has no direct energy losses and no energy-use impacts on the rest of the system.)
DE is delivery effectiveness, defined as the ratio of heat/cooling output from the ducts to heat/cooling input into the ducts.

Fequip is equipment efficiency factor, defined as the ratio of equipment efficiency in the system under evaluation to what the equipment efficiency would be with a perfect duct system.

Fload is load factor, defined as the ratio of heating/cooling load with a perfect duct system to the heating/cooling load in the system under evaluation.

Equation (1) was later modified somewhat for use in Standard 152P, but it remains the most readily understood general definition of distribution efficiency.

One of the objectives of ASHRAE research project 1165-RP -- and the subject of this paper -- was to determine the functional forms of the equipment efficiency factors in Standard 152. Other objectives of the project were to quantify impacts of thermosiphoning, continuous fan operation, and zone control on duct efficiency. A future paper on those topics is planned.

In Standard 152P as it currently exists (ASHRAE 2001), values of Fequip are approximated, either as a constant 1.0 for single-capacity equipment, or as a linear function of delivery effectiveness for variable-capacity equipment. This formulation has several shortcomings. First, since delivery effectiveness does not include interactions between the duct system and the load (principally thermal regain and uncontrolled air infiltration caused by duct leaks), equipment efficiency factors provided in the standard can’t include these interactions either. Second, any part-load efficiency degradation is not considered in the calculation, because of the steady-state assumption. Third, it is assumed that the number of hours of system operation is the same for both perfect and real ducts (Walker, 1998). In reality, as duct system energy losses increase, the number of hours of operation can become much larger than with perfect ducts. Although the assumptions made by Standard 152P simplify the calculation and may be better than ignoring duct-equipment interactions altogether, a comprehensive study was needed to examine the interactions of these factors to obtain more accurate values of Fequip.

The objective of this paper is to provide more accurate values of Fequip for single-capacity equipment and formulas to calculate Fequip for variable-capacity equipment. These values and formulas are based on simulations using a detailed computer duct model, FSEC 3.0, recommended by ASHRAE research project 865-RP (Gu et al. 1998a). The selected parameters used in this study are home type, duct system location (e.g. attic, crawl space and basement), climate, equipment type and equipment capacity.

In order to consider system interactions, it is necessary first to provide the theoretical basis for the relationship between distribution system efficiency and the equipment efficiency factor. The second step is to determine whether we need to use the current calculation method provided in Standard 152P or recommend a new method to calculate distribution system efficiencies using modified equipment efficiency factors.

EQUIPMENT EFFICIENCY FACTORS

As noted earlier, ASHRAE Standard 152P originally used the load factor to account for the impact of both thermal regain and infiltration, but in the course of developing the standard, this was changed somewhat. The reason for the change was to make it easier to handle the fact that the thermal regain depends on supply and return conduction losses and on supply leakage losses, but not on return leakage losses. The thermal regain was removed from the load factor and made part of a “corrected” Delivery Effectiveness. The load factor now accounts only for infiltration.

The following equation is used in Standard 152P to calculate distribution system efficiency:

ndist = DEcorr * Fequip * Fload * (1 - Fcycloss) (2)

where ndist and Fequip are defined as in Equation 1. DEcorr differs from DE in that the thermal regain correction is added, Fload differs from Fload in that it only includes the impact of infiltration effects, and Fcycloss separates out the impact of off-cycle heat losses in the ducts.

It should be pointed out that the infiltration factor, Fload used in Eq. (2), is different from the load factor Fload defined in Eq. (1). Combining Eqs. (1) and (2), one may conclude:

DEcorr * Fload * (1 - Fcycloss) = DE * Fload (3)

Although both Eqs. (1) and (2) can be used to calculate distribution system efficiencies, we prefer to use Eq. (1) as a formula to calculate distribution system efficiencies because it is derived from first principles. The detailed derivation is available in the final report (Gu et al. 2001). The biggest difference is that Standard 152P uses three individual items of system interactions: thermal regain, infiltration loss due to unbalanced duct leakage and equipment part load energy loss, while in Eq. (1), we have combined all three system interactions in one item.

The simulation results provided a basis for deriving regression equations that show Fequip is a function of DE*Fload (accounting for system interactions), instead of just DE as it is now used in Standard 152P. The results could easily be translated into the current format of Standard 152 using Equation (3). That is, DE*Fload could be replaced by DEcorr * Fload * (1 - Fcycloss) should ASHRAE wish to use our results in a future version of Standard 152.

SIMULATION CHARACTERISTICS

This section provides parameters used in simulations to examine interactions among air distribution systems, cooling and heating equipment performance, and building envelope response. The parametric variations consist of house types, climates, duct system configurations and associated leakage and insulation levels, and equipment types and nominal equipment sizes.

House types

Three types of residences were selected for this project. They include homes with slab-on-grade, crawl space and basement. The house type is climate dependent, shown in Table 1.

Climates

TMY weather data were used in simulations. The heating dominated climate of Minneapolis was used to simulate a heating season. The cooling dominated climate of Miami was used to simulate a cooling season. Baltimore weather data was used to simulate both cooling and heating seasons.

Duct configuration

Five duct configurations are used. Table 1 lists the duct configurations, associated home types and corresponding climates.

TABLE 1
Duct configuration determination

Duct location	House type	Climate	Season
Attic	Slab-on-grade	Miami	Cooling
Crawl space	Crawl space	Baltimore	Cooling and heating
Basement	Basement	Minneapolis	Heating
Half in attic and half in crawl space	Crawl space	Miami and Baltimore	Heating and cooling
Half in attic and half in basement	Basement	Minneapolis	Heating

The first three duct configurations are commonly used in houses with corresponding foundation types. Although the last two duct configurations may not represent physical reality, they are useful as a computer abstraction for estimating interactions between duct systems and equipment to cover impacts of both duct systems above the ceiling and below the floor.

Duct leakage

Four duct leakage configurations are used as indicated in Table 2.

TABLE 2
Duct leakage

Case	Supply leak (%)	Return leak (%)	Note
1	0	0	Perfect duct
2	5	10	Return dominant leakage
3	10	10	Balanced leakage
4	10	5	Supply dominant leakage

Note: Leakage indicated above is the percentage of total fan flow.

Case 1 is a perfect duct system, with very high resistance (R-500) duct insulation and no duct leakage. This case is used as the reference case to calculate distribution system efficiencies and equipment efficiency factors for the other cases. Case 2 is designed with a return leak dominant duct system. Field research has indicated that a supply leak of 5% of the total fan flow with a return leak of 10% of the total fan flow is the most common in existing Florida homes (Cummings et al., 1991). Case 3 is designed to have a balanced leaky duct system with the same amount of supply and return leaks. Case 4 is designed to be a supply dominant leakage system.

Duct insulation levels

Four levels of duct insulation and associated home types are listed in Table 3.

TABLE 3
Duct insulation levels

Case	Duct insulation m2.K/W (ft2.h.oF/Btu)	Home foundation type
1	0 (0)	Basement
2	0.74 (4.2)	Slab-on-grade, crawl space, basement
3	1.06 (6)	Slab-on-grade, crawl space, basement
4	1.76 (10)	Slab-on-grade, crawl space

Equipment type

Seven types of heating equipment and four types of cooling equipment are used in this task. These equipment types are summarized in Table 4.

TABLE 4
Cooling and heating equipment types

Equipment Type	Efficiency	Usage	Location
Single capacity AC	SEER 10 & 14	Cooling	Miami & Baltimore
Two speed AC	SEER 17.6	Cooling	Miami & Baltimore
Single capacity HP with backup electric heater	HPSF 8.0	Heating	Baltimore & Minneapolis
Two speed HP with backup electric heater	HPSF 8.8	Heating	Baltimore & Minneapolis
Natural vent gas furnace	AFUE 65	Heating	Baltimore & Minneapolis
Power combustion gas furnace	AFUE 78	Heating	Baltimore & Minneapolis
Direct vent gas furnace	AFUE 62	Heating	Baltimore & Minneapolis
Two stage gas furnace	AFUE 73	Heating	Baltimore & Minneapolis
Condensing gas furnace	AFUE 91	Heating	Baltimore & Minneapolis

PROGRAM SELECTION AND EQUIPMENT MODEL DEVELOPMENT

The model used here was selected based on recommendations of the ASHRAE project 852-RP (Gu et al. 1998a) and validation (Gu et al. 1998b). The sub-model of single capacity AC was already available in the FSEC 3.0 model. The sub-models of two speed air conditioners and single and two speed heat pumps were developed based on performance data provided by manufacturers. It should be pointed out that defrost controls were not considered in this research. It is expected that energy use would increase, while equipment output load has little impact, if defrost was considered. The gas furnace sub-models were integrated from the SP43 program (Jakob et al. 1986).

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RESULTS FOR SINGLE CAPACITY EQUIPMENT

Single capacity equipment used in this study consists of single speed air conditioners and gas furnaces. Equipment efficiencies are mainly dependent on part load performance, which causes equipment efficiency degradation when hourly building load is less than a full capacity of equipment. Equipment efficiency slightly increases with increasing part load ratio. Since the part load ratio with leaky ducts is higher than with perfect ducts, the equipment efficiency with leaky ducts is also higher. It should be pointed out that this “efficiency increase” does not translate to lower energy use but, rather, is an aberration caused by the definition of the term “Fequip” whereby the building load is allowed to independently vary in the numerator and denominator of the ratio.

Table 5 lists seasonal Fequip values averaged over three levels of duct insulation and leakage in different equipment types, climates and duct locations. “Split” used in the table means that a duct system is divided into two identical parts, one is above the ceiling and the other is below the floor. It is clear that Fequip values are slightly larger than 1.0. We recommend Fequip = 1.02, because the value of.1.0 is biased. The exception is that in cases of split ducts under cooling conditions, Fequip values are larger than 1.08. It should be pointed out that fixed nominal equipment sizes are applied to cases of single and split duct locations. The cooling equipment used in split duct systems is slightly oversized, because of smaller cooling loads. The impacts of part load energy losses makes Fequip larger.

TABLE 5
Averaged Fequip using single capacity heating and cooling equipment

Equipment type	Efficiency	Usage	Location	Duct location	Fequip
Single Capacity AC	SEER 10	Cooling	Miami	Attic	1.027
Single Capacity AC	SEER 14	Cooling	Miami	Attic	1.028
Single Capacity AC	SEER 10	Cooling	Baltimore	Crawl space	1.026
Single Capacity AC	SEER 14	Cooling	Baltimore	Crawl space	1.038
Natural vent gas furnace	AFUE 65	Heating	Baltimore	Crawl space	1.005

Power combustion gas furnace	AFUE 78	Heating	Baltimore	Crawl space	1.004
Direct vent gas furnace	AFUE 62	Heating	Baltimore	Crawl space	1.005
Two stage gas furnace	AFUE 73	Heating	Baltimore	Crawl space	1.002
Condensing gas furnace	AFUE 91	Heating	Baltimore	Crawl space	1.009
Natural vent gas furnace	AFUE 65	Heating	Minneapolis	Basement	1.003
Power combustion gas furnace	AFUE 78	Heating	Minneapolis	Basement	1.002
Direct vent gas furnace	AFUE 62	Heating	Minneapolis	Basement	1.003
Two stage gas furnace	AFUE 73	Heating	Minneapolis	Basement	1.012
Condensing gas furnace	AFUE 91	Heating	Minneapolis	Basement	1.013
Single Capacity AC	SEER 10	Cooling	Miami	Split	1.094
Single Capacity AC	SEER 14	Cooling	Miami	Split	1.112
Single Capacity AC	SEER 10	Cooling	Baltimore	Split	1.081
Single Capacity AC	SEER 14	Cooling	Baltimore	Split	1.100
Natural vent gas furnace	AFUE 65	Heating	Baltimore	Split	1.011
Power combustion gas furnace	AFUE 78	Heating	Baltimore	Split	1.011
Direct vent gas furnace	AFUE 62	Heating	Baltimore	Split	1.011
Two stage gas furnace	AFUE 73	Heating	Baltimore	Split	1.011
Condensing gas furnace	AFUE 91	Heating	Baltimore	Split	1.018
Natural vent gas furnace	AFUE 65	Heating	Minneapolis	Split	1.004
Power combustion gas furnace	AFUE 78	Heating	Minneapolis	Split	1.004
Direct vent gas furnace	AFUE 62	Heating	Minneapolis	Split	1.004
Two stage gas furnace	AFUE 73	Heating	Minneapolis	Split	1.007
Condensing gas furnace	AFUE 91	Heating	Minneapolis	Split	1.022

RESULTS FOR VARIABLE CAPACITY EQUIPMENT

Variable capacity equipment used in this study consists of two speed air conditioners and single and two speed heat pumps with backup electric heaters. In general, equipment efficiency factors with variable capacity equipment are less than 1.0, because the equipment operates in a higher efficiency mode with perfect ducts and at a lower efficiency mode with leaky ducts. This is due to more complex relationships between capacities and equipment energy uses. A two speed air conditioner has two different efficiencies, a higher efficiency at low speed and a lower efficiency at high speed. The equipment operation mode is dependent on nominal equipment size and building load. It also depends on thermostat type and settings (such as setbacks), as well as control algorithms in the equipment firmware. These additional dependences are not addressed in this project because they are beyond of scope of the work.

A single speed heat pump also has two efficiencies, one is from the heat pump itself, while the other is from the backup electric heater. A two speed heat pump has three efficiencies, the highest one is from low speed operation, the middle one is from high speed operation, while the lowest is from backup electric heater operation.

Tables 6 lists seasonal Fequip values averaged over three levels of duct insulation and leakage in different equipment types, climates and duct locations, for two speed air conditioners and single capacity and two speed heat pumps, respectively. It should be pointed out that the fixed sizes of heating and cooling equipment were also used in simulations. Fequip values are greater than 1.0 in some cases, but less than 1.0 in most cases. The main reason is due to a ratio of building load to equipment capacity, which determines which operating mode occurs. Therefore, the nominal equipment size is also an important factor in determining equipment efficiency factors. For example, if the equipment is undersized, the equipment tends to operate at high speed most of the time for both perfect and real ducts. The equipment efficiency factor is slightly larger than 1.0. If the equipment is oversized, the equipment operates at low speed most of the time for both perfect and leaky ducts. The equipment efficiency factor may also be slightly larger than 1.0. When the equipment is sized correctly, it is expected to operate at high speed mode with leaky ducts and at low speed mode with perfect ducts most of the time. Fequip is less than 1.0. The equipment efficiency factor may reach the lowest value when the equipment operates most of the time at low speed with perfect ducts and at high speed with leaky ducts. The lowest value is equal to a ratio of low efficiency to high efficiency.

TABLE 6
Averaged Fequip using variable capacity heating and cooling equipment

Equipment type	Efficiency	Usage	Location	Duct location	Fequip
Two speed AC	SEER 17.6	Cooling	Miami	Attic	0.967
Two speed AC	SEER 17.6	Cooling	Baltimore	Crawl	0.944
Two speed AC	SEER 17.6	Cooling	Miami	Split	1.024
Two speed AC	SEER 17.6	Cooling	Baltimore	Split	0.966
Single speed HP	HSPF 8.0	Heating	Baltimore	Crawl space	1.051
Two speed HP	HSPF 8.8	Heating	Baltimore	Crawl space	0.971
Single speed HP	HSPF 8.0	Heating	Minneapolis	Basement	0.962
Two speed HP	HSPF 8.8	Heating	Minneapolis	Basement	0.941
Single speed HP	HSPF 8.0	Heating	Baltimore	Split	1.051
Two speed HP	HSPF 8.8	Heating	Baltimore	Split	0.944
Single speed HP	HSPF 8.0	Heating	Minneapolis	Split	0.904
Two speed HP	HSPF 8.8	Heating	Minneapolis	Split	0.870

VARIABLE CAPACITY EQUIPMENT WITH VARIABLE NOMINAL SIZES

In order to provide more accurate values of Fequip, an additional parameter, nominal equipment size, should be introduced in the equipment efficiency factor calculation. The nominal equipment size is defined as the capacity at high speed at ARI conditions. Additional simulations were performed to quantify the impact of nominal equipment size on Fequip. The following parametric variations were considered.

TABLE 7
Nominal equipment sizes selected in simulations

Climate	Equipment	Operation	Nominal size kW (ton)	Relative size
Miami & Baltimore	Two speed AC	Cooling	8.44 (2.4)	80%
			9.49 (2.7)	90%
			10.5 (3.0)	100%
Baltimore	Single and two speed HP	Heating	8.44 (2.4)	80%
			10.5 (3.0)	100%
			13.2 (3.75)	125%
			15.8 (4.5)	150%
			31.6 (9.0)	300%

A discussion of the results obtained from the simulations follows.

Two Speed Air Conditioners

A curve fit of equipment efficiency factors as a function of DE*Fload (defined in Eq. 2) showed that a linear function is adequate in the range 0.7 to 0.9 However, after we included an additional point with Fequip = 1 at DE=1, it was observed that a quadratic function of DE*Fload was a better choice for the full range. The quadratic curves are upward for larger nominal equipment sizes, and downward for smaller nominal equipment sizes. The result was the following regression equation:

Fequip = a + b*(DE*Fload) + c*(DE*Fload)2 (4)

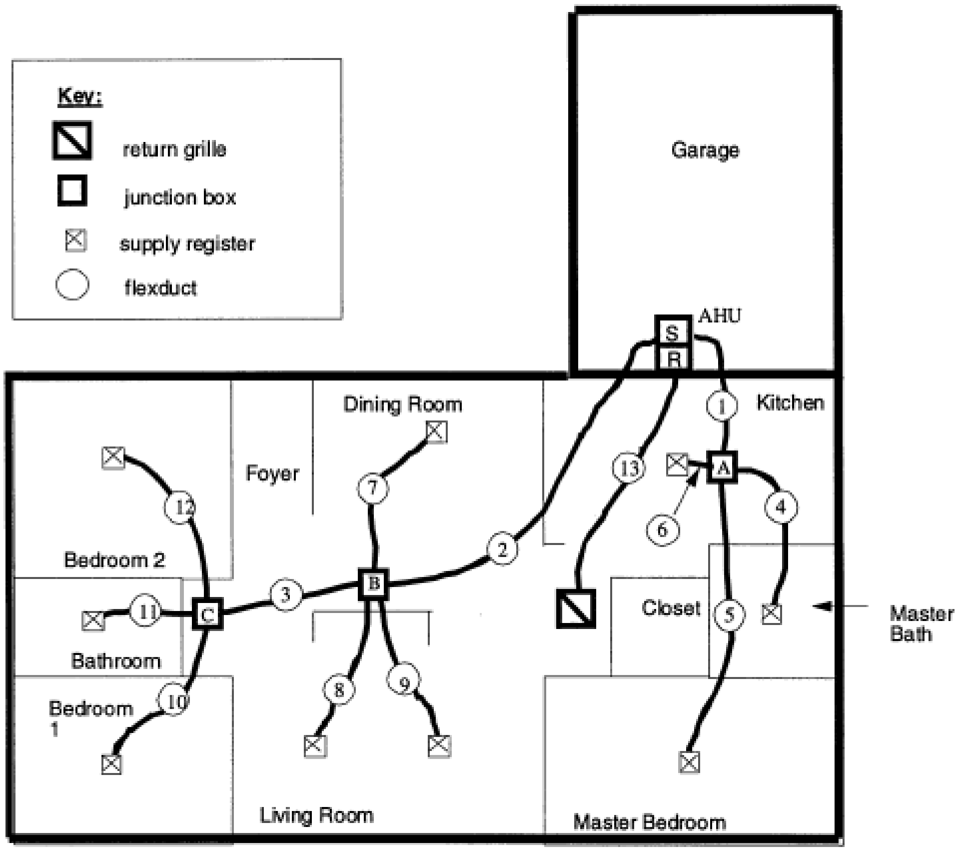
where

a, b, c Constants
DE Delivery effectiveness [0-1]
Fload Load factor defined in this study

Table 8 shows regression coefficients and associated r2 for a two speed air conditioner:

TABLE 8
Cooling regression coefficients and associated r2 for a two speed AC

Location	Duct	Rel Size	c	b	a	r^2
Miami	Attic	80%	0.276	-0.051	0.775	0.99
Miami	Attic	90%	-1.109	2.320	-0.210	0.97
Miami	Attic	100%	-4.394	7.882	-2.488	0.93
Baltimore	Crawl	80%	0.477	-0.365	0.887	1.00
Baltimore	Crawl	90%	0.077	0.257	0.666	1.00
Baltimore	Crawl	100%	-1.126	2.246	-0.120	1.00
Miami	Split	80%	0.640	-0.744	1.104	0.96
Miami	Split	90%	-0.722	1.453	0.269	0.80
Miami	Split	100%	3.200	5.501	-1.300	0.66
Baltimore	Split	80%	0.380	-0.230	0.850	0.99
Baltimore	Split	90%	-0.384	1.037	0.347	0.99
Baltimore	Split	100%	-1.778	3.356	-0.578	0.99



House Characteristics:

- 1500 sq. ft. (conditioned space)
- floor construction varies by climate
- frame walls with insulation level suitable for climate
- ceiling insulation suitable for climate
- 224 sq. ft. windows equally distributed on each side of the house
- roof: hip gable, shingled, medium color no roof overhang
- duct construction and location suitable for climate
- equipment capacity suitable for climate

Figure 1 *Prototype house floor plan and layout of air distribution system.*

Figure 2 shows seasonal cooling Fequip vs. DE*Fload for attic duct configuration using a two speed AC in Miami. “Pred xx% Rel size” in the legend stands for predicted results with xx% relative nominal equipment size defined in Table 7. Symbols represent Fequip obtained from simulations for different nominal equipment sizes, duct insulation levels and leaks. The solid line is the equation from Standard 152P (Eq. 24 in Walker, 1998). The applicable Standard 152P equation is:

Fequip = 0.83 + 0.17*DE (5)

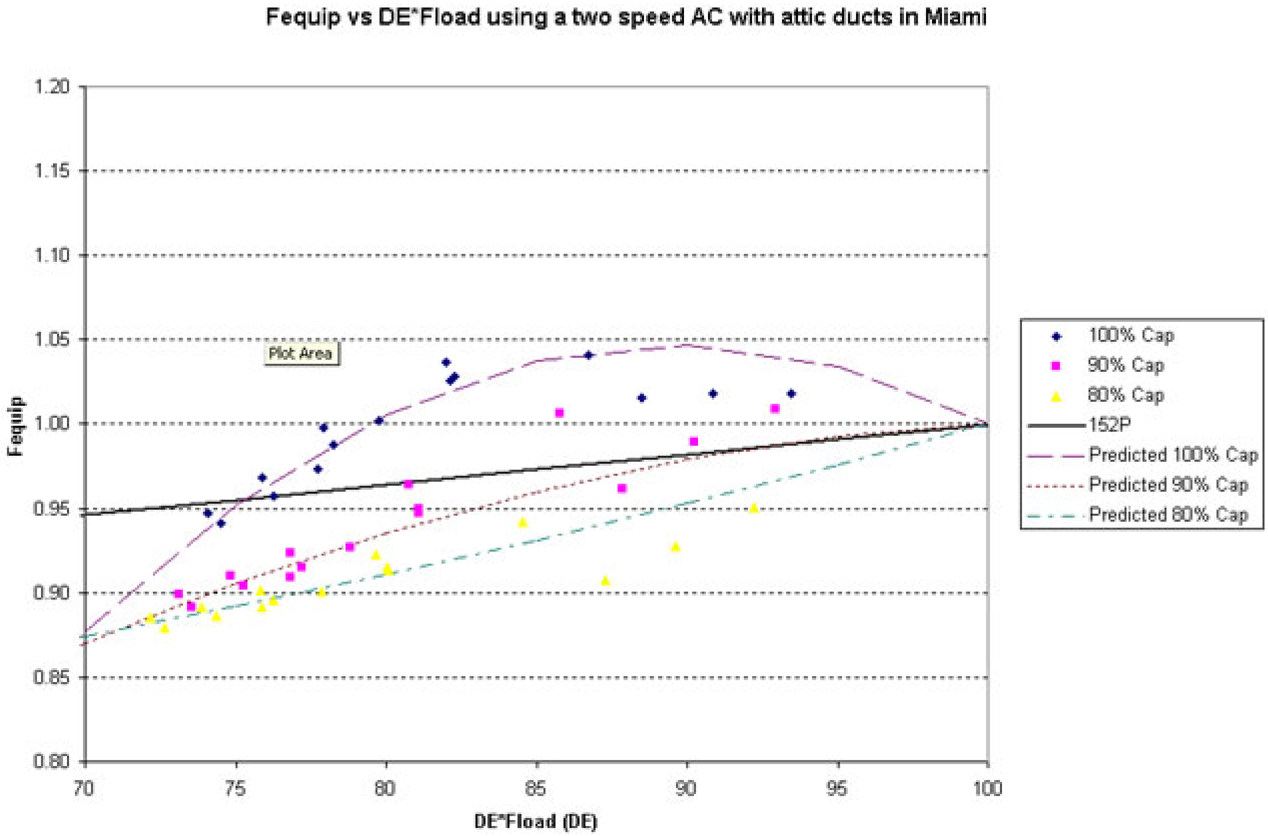


Figure 2

The non-solid lines are the curve fit equations developed in the present work. It is worth noting that DE is the independent variable for the solid line that is obtained using the equation from Standard 152P, while DE*Fload is the independent variable for the curve fit derived in the present work. In this figure, the 152P line appears to be a fair representation of the data points of the present work. The non-solid lines in the figure use the regression equations developed in this study whose coefficients are listed in Table 8. In general, when DE*Fload is less than 0.8, Fequip values are less than unity for a relative nominal equipment size of 100%. This is because the equipment tends to operate in the high speed mode when leaky ducts are present, and in the low speed mode when perfect ducts are present. However, with increasing duct system efficiency, building loads will be lower, and the equipment will tend to operate at the same low speed mode for both perfect and the less leaky duct configurations. Fequip in these cases are slightly larger than unity and the resulting curve is upward. When relative equipment size is reduced to 90% and 80%, seasonal cooling Fequip values are lower than unity in most cases and the curve tend to be downward (example the curve for 80% size). The linear equation provided in Standard 152P, clearly, does not adequately predict Fequip, since the impact of system interactions and nominal equipment sizes are not considered in the equation from the standard. Quadratic curves using DE*Fload appear to fare better.

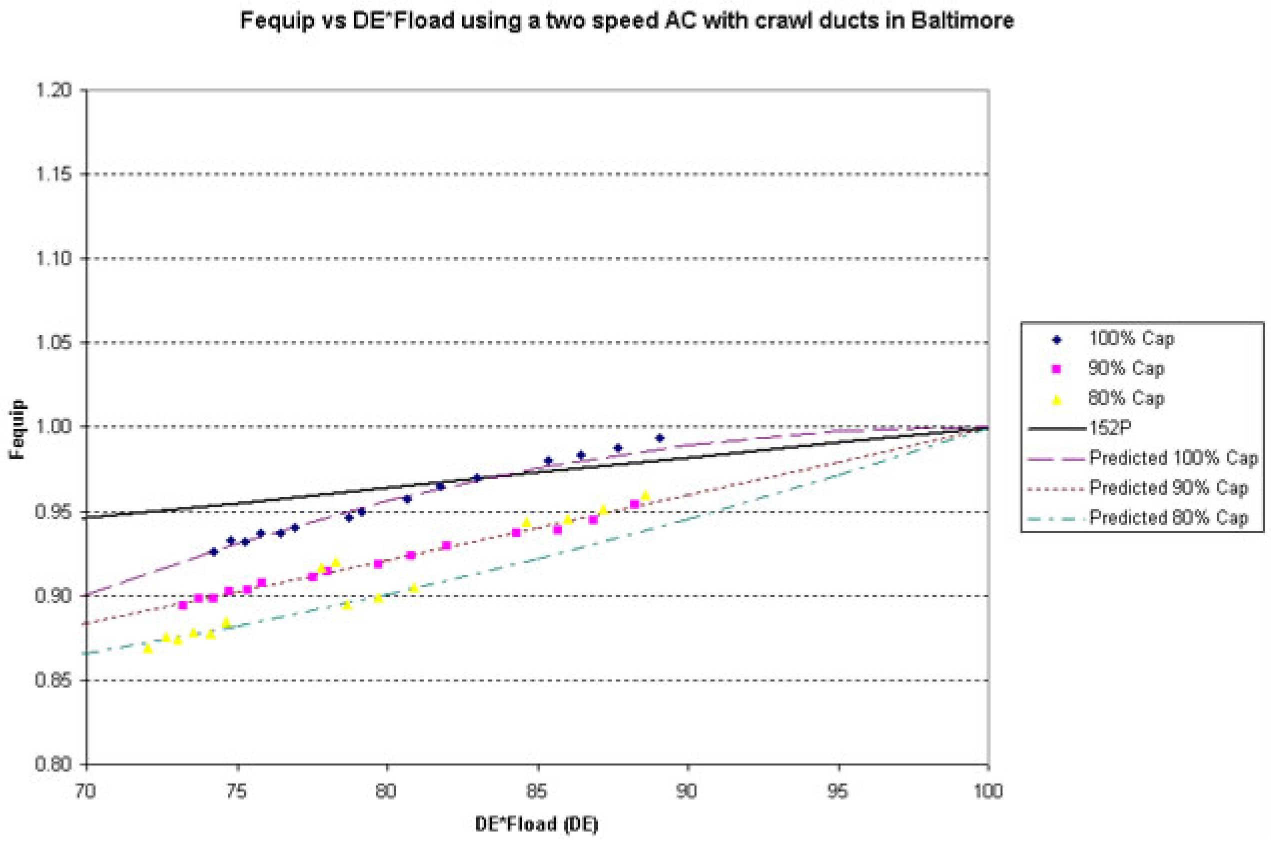


Figure 3

Figure 3 shows seasonal cooling Fequip vs. DE*Fload for the crawl space duct configuration using two speed AC in the Baltimore climate. The equipment operates in high speed mode with leaky ducts and in low speed mode with perfect ducts resulting in Fequip values that are lower than unity. The 152P method generally over-predicts Fequip, compared to the equation derived in the present work.

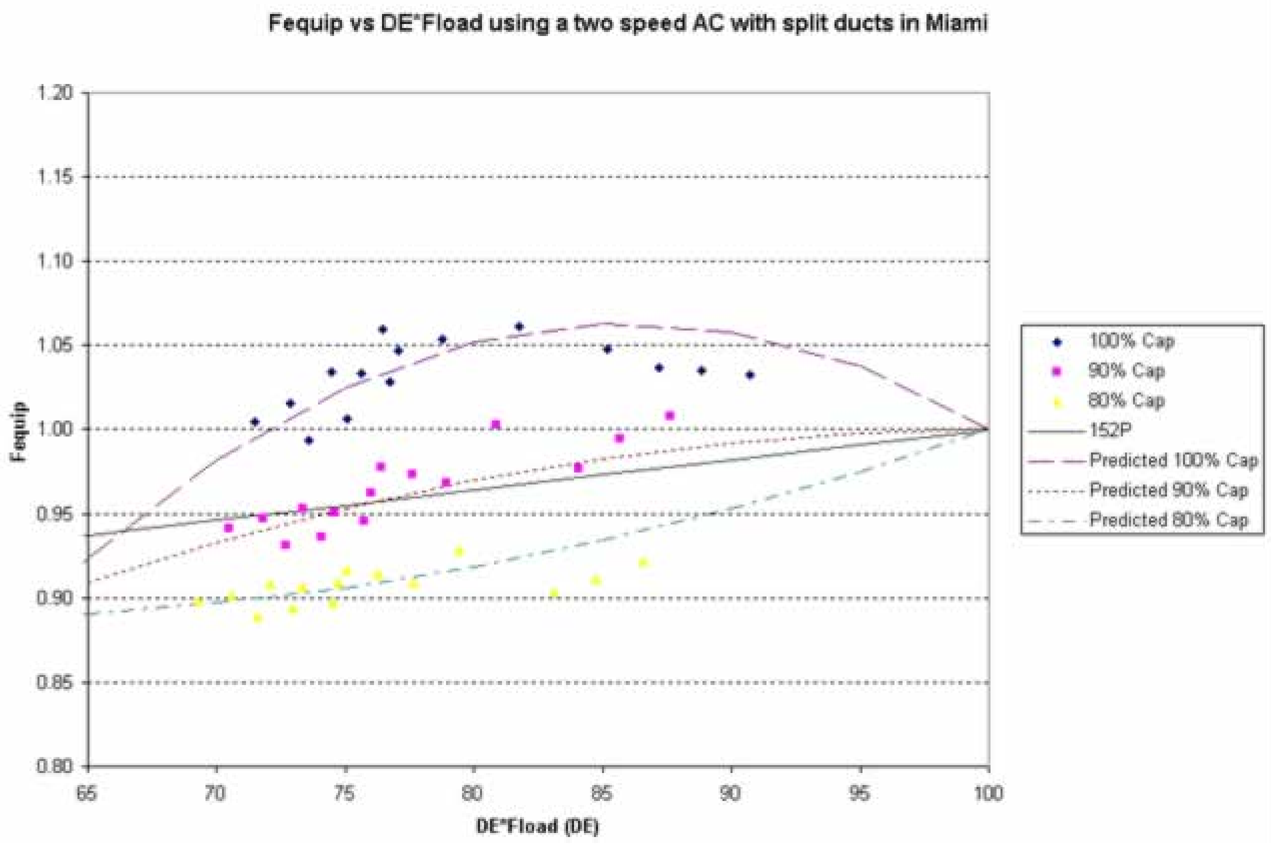


Figure 4

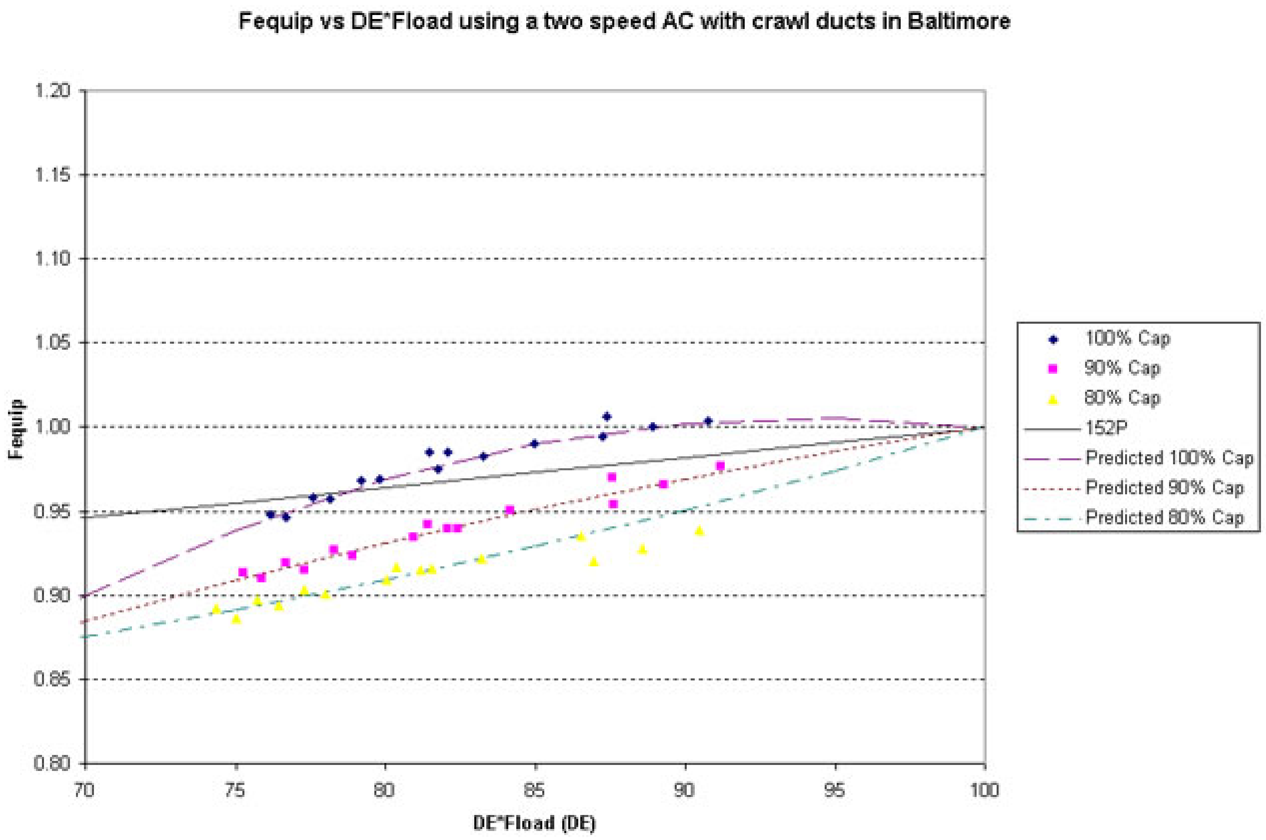


Figure 5

Figures 4 and 5 show similar results for the split duct configuration in Miami and Baltimore climates, respectively. The trends are similar to those with attic and crawl space duct configuration for the same climates.

Clearly, these results indicate that Fequip is also climate dependent. One simplified equation such as the one in the152P standard cannot address the climatic variation adequately.

Single and Two Speed Heat Pumps

Seasonal heating equipment efficiency factors were also found to have the similar linear relationship with DE*Fload in the range 0.6 to 0.9. Adding another data point, Fequip = 1 at DE=1, showed that a quadratic relationship between Fequip and DE*Fload was a better fit. The regression, so derived, is the same as Eq. (4). Table 9 shows regression coefficients and associated r2 for heat pumps. Rel size in the table stands for relative size.

TABLE 9
Heating regression coefficients and associated r2 for heat pumps in Baltimore

Type	Duct	Rel size	c	b	A	r^2
Single	Crawl	80%	-0.6303	1.0308	0.5954	0.61
Single	Crawl	100%	-0.5422	0.7094	0.8283	0.83
Single	Crawl	125%	-0.5766	0.5927	0.9797	0.96
Single	Crawl	150%	-0.4444	0.2467	1.1927	0.98
Single	Crawl	300%	0.0509	-0.8177	1.7675	0.99
Two	Crawl	80%	-0.6360	1.2548	0.3775	0.95
Two	Crawl	100%	-0.6587	1.1485	0.5064	0.77
Two	Crawl	125%	-0.8775	1.3054	0.5679	0.63
Two	Crawl	150%	-0.7361	0.8845	0.8444	0.90
Two	Crawl	300%	-0.2335	-0.2740	1.5058	0.97

Single	Split	80%	-0.7155	1.1717	0.5374	0.72
Single	Split	100%	-0.6687	0.9275	0.7340	0.66
Single	Split	125%	-0.5576	0.5739	0.9793	0.92
Single	Split	150%	-0.5739	0.4504	1.1144	0.93
Single	Split	300%	-0.2267	-0.3589	1.5812	0.99
Two	Split	80%	-0.6831	1.3345	0.3436	0.93
Two	Split	100%	-0.7347	1.2825	0.4464	0.86
Two	Split	125%	-0.9120	1.3710	0.5376	0.60
Two	Split	150%	-0.9833	1.2906	0.6838	0.69
Two	Split	300%	-0.4673	0.0869	1.3742	0.97

Figure 6 shows seasonal heating Fequip for the crawl space ducts configuration for a single speed heat pump with backup electric heater for different nominal equipment sizes, duct insulation levels and leaks in the Baltimore climate. Fequip vs. DE calculated using Eq. (6) of Standard 152P (Eq. 26 in Walker, 1998) is plotted as a solid line. The applicable Standard 152P equation is:

Fequip = 0.44 + 0.56*DE (6)

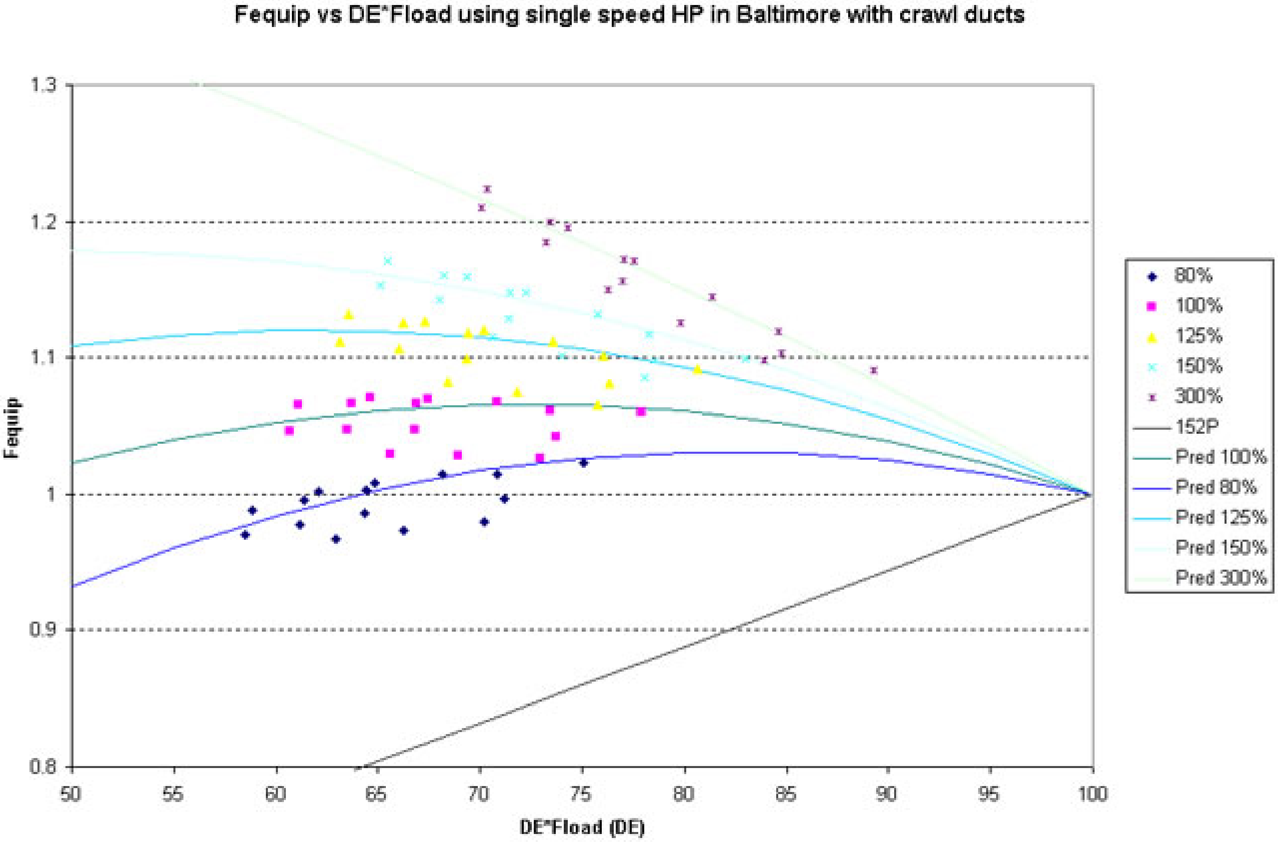


Figure 6

Results show that Fequip values are larger than unity when the relative nominal equipment size is 100% or more. This is due to lower heating loads associated with milder climates, since the backup electric heater rarely comes on for both leaky and perfect ducts. However, for lower relative nominal equipment sizes, (e.g. 80%), the electric heater is “on” more often resulting in Fequip values below unity. This, again, demonstrates the dependence of Fequip on the nominal equipment size chosen. The Standard 152P methodology tends to under-predict Fequip and the discrepancy between 152P and the equation derived in the present work is significantly large.

Figure 7 shows seasonal heating Fequip for the crawl space duct configuration using a two speed heat pump with backup electric heater as a function of different nominal equipment sizes, duct insulation levels and leaks for the Baltimore climate. For larger nominal equipment sizes, Fequip is greater than unity, since the heat pump operates at high speed mode for both perfect and leaky ducts, while for smaller nominal equipment sizes, Fequip is lower than unity, since the heat pump operates in varying modes for perfect and leaky ducts. The Standard 152P methodology under-predicts Fequip compared to the results of the present work.

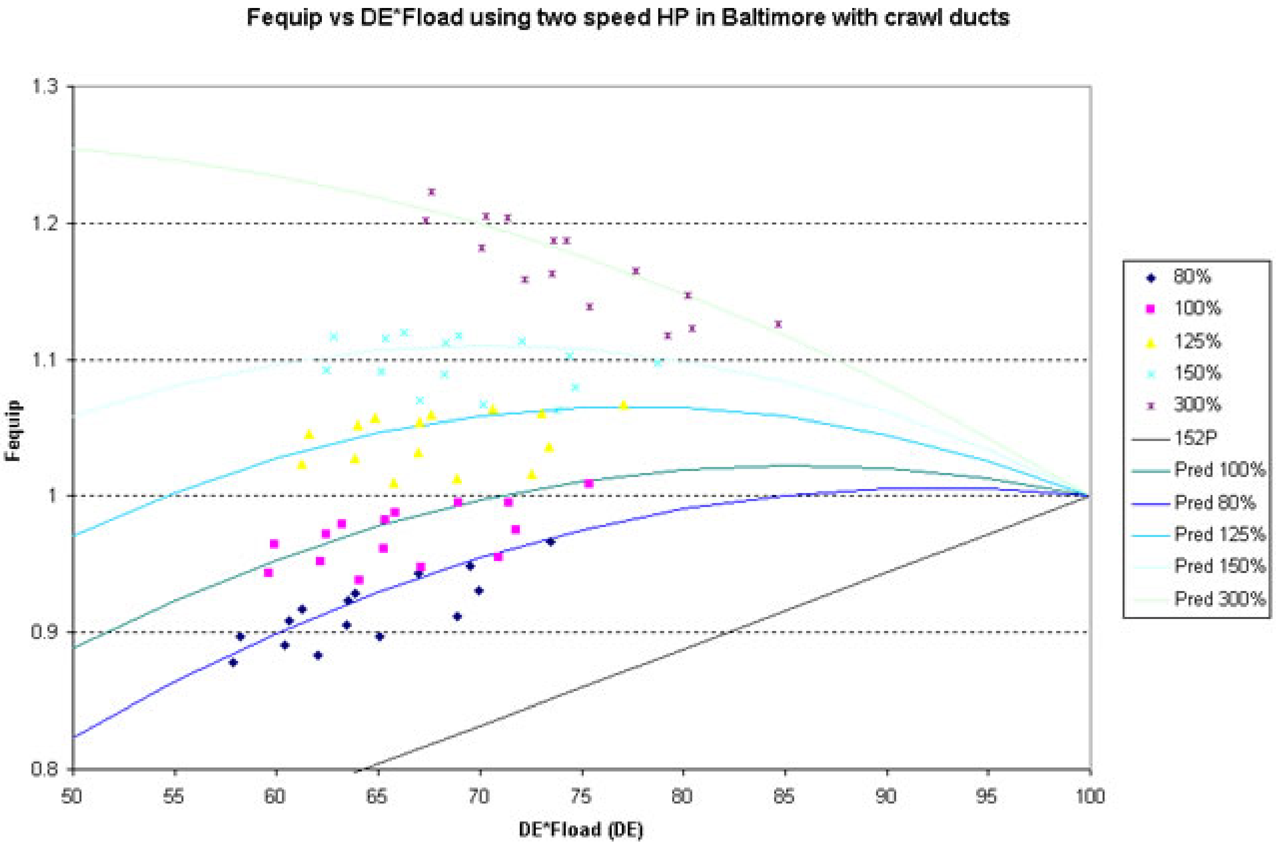

Fequip vs DE*Fload using two speed HP in Baltimore with crawl ducts

Figure 7

Figures 8 and 9 show seasonal heating Fequip with the split duct configuration using single and two speed heat pumps, respectively, in the Baltimore climate. The trends are similar to the crawl space duct configuration.

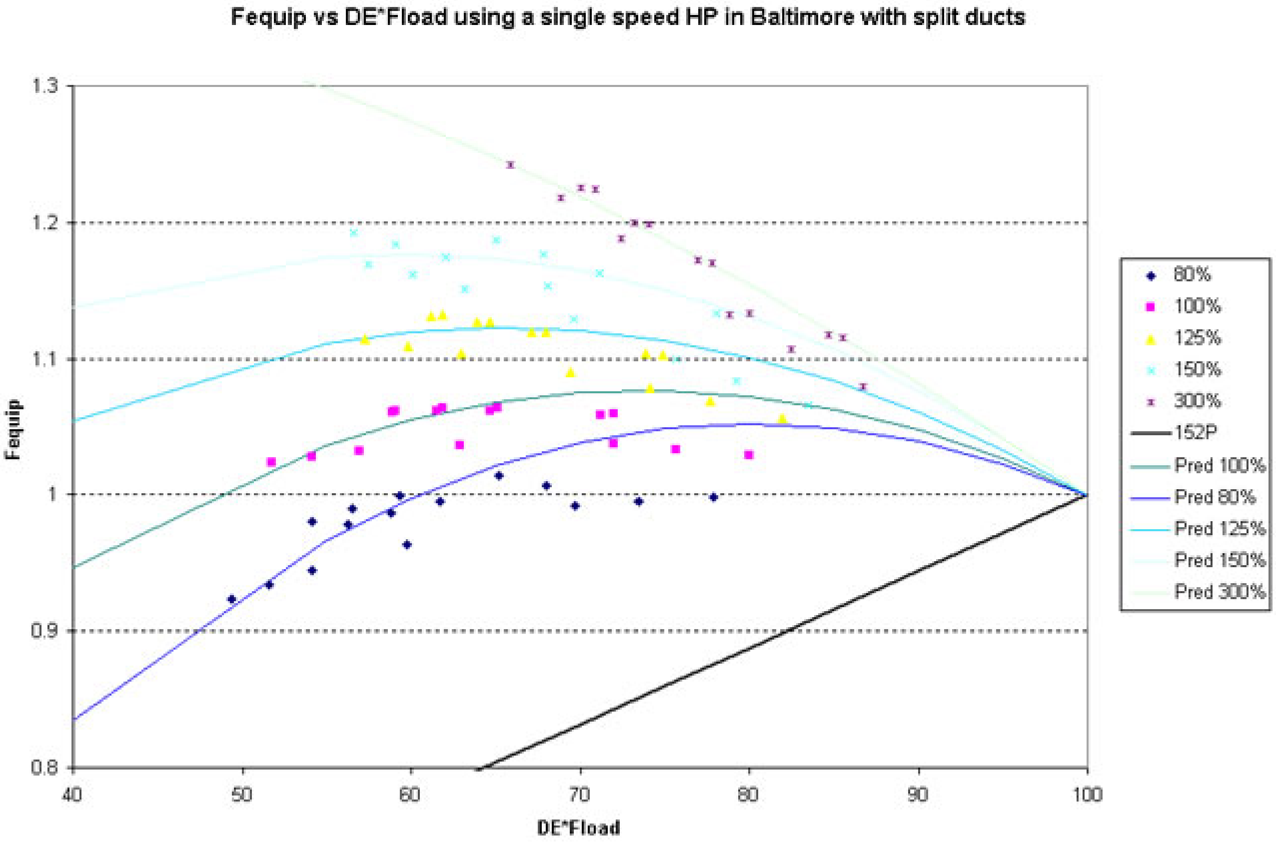

Fequip vs DE*Fload using a single speed HP in Baltimore with split ducts

Figure 8

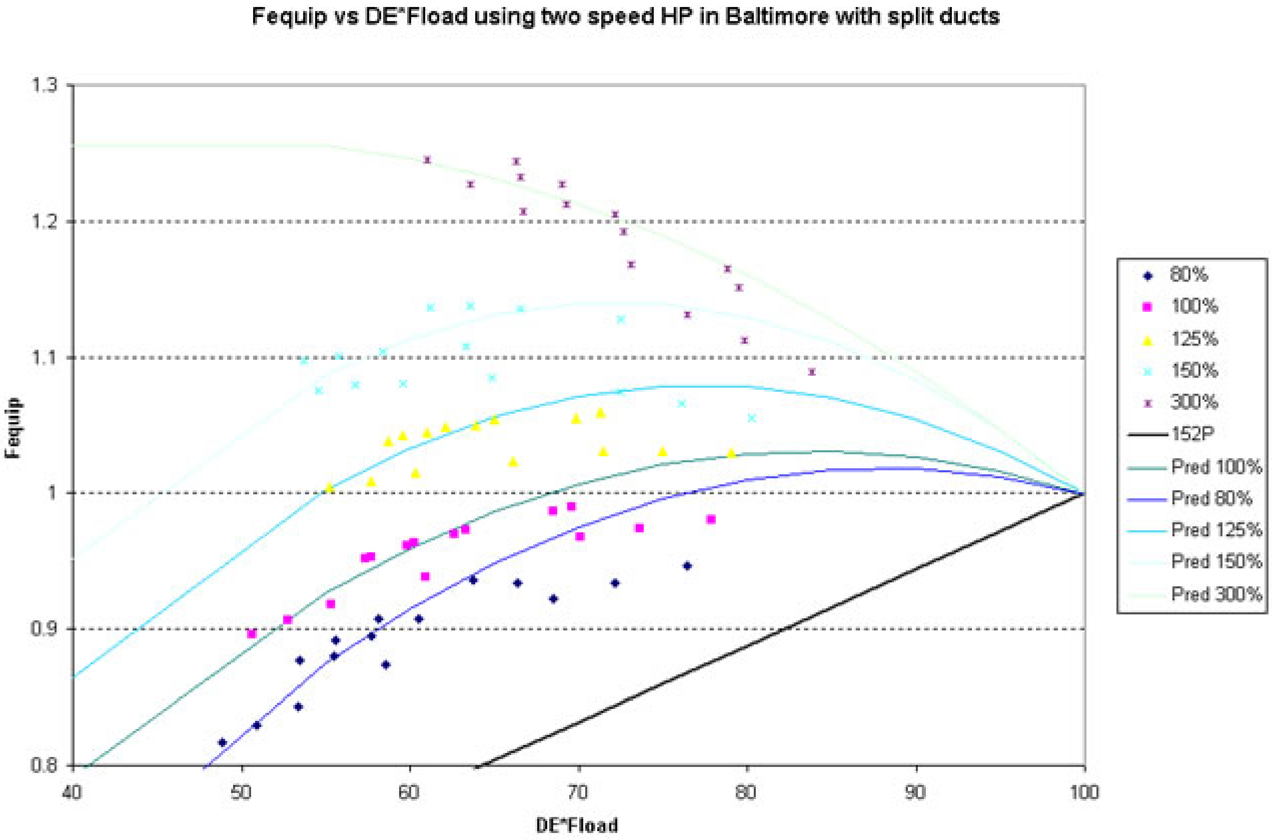


Figure 9

CONCLUSIONS AND RECOMMENDATIONS

- Results of the present work clearly show that DE*Fload is a better independent variable for determining Fequip, since it includes both the impacts of duct system efficiency and interactions among air distribution systems, cooling and heating equipment performance and building envelope response. As a result, the quadratic function derived in the present work is suggested as the better approach to determine Fequip and is recommended, for inclusion in the ASHRAE Standard 152P.
- Single capacity equipment has a simple relationship between coil output and power consumption. Fequip values are nearly unity for this type of equipment. Although either methodology -- the present work or the 152P – may be used, it is recommended Fequip=1.02 based on the present work. With very few exceptions, such as for cases of equipment over sizing, their predictions are similar.
- Variable capacity equipment has more complex relationships between coil output and power consumption. Equipment efficiency is affected not only by coil output and part load ratio, but also by the nominal equipment size chosen and operating range. The simplified equation in 152P is inadequate. The quadratic equation derived in the present work for both heating and cooling Fequip is decidedly more reasonable. Fequip values calculated using equations in 152P are significantly different from the present work.
- Additional climate ranges should be considered to establish a more general regression equation to predict equipment efficiency factors which includes climate as one of the independent variables. Cooling or heating degree days could perhaps serve as the independent variable.

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Lixing Gu is principal research engineer, Muthusamy V. Swami is program director and Philip W. Fairey is deputy director at Florida Solar Energy Center