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System Interactions in Forced-Air Heating and Cooling Systems, Part II: Continuous Fan Operation

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ABSTRACT

The purpose of continuous fan operation is to bring in fresh outdoor air to the conditioned space in order to maintain acceptable indoor air quality. Ventilation not only uses more energy, but it also impacts air distribution system efficiency. This is partially due to various system interactions. The objective of this paper is to quantify the impact of continuous fan operation on energy use and distribution efficiency by introducing two new parameters: energy use ratio (EUR) and distribution efficiency ratio (DER). EUR is defined as a ratio of the total energy use with the outdoor air system to that without the outdoor air system. DER is defined as a ratio of distribution efficiency with the outdoor air system to that without the outdoor system. DER is represented by a ratio of EURs with perfect ducts to those with real ducts. Both ratios are multipliers used to predict energy use and distribution efficiency with the outdoor air system when energy use and distribution efficiency without the outdoor air system are known. Regression equations were developed by performing statistical analysis on the simulation results. Seasonal EUR was found to be a function of equipment efficiency, ventilation rate, envelope tightness, duct leakage, and insulation levels. Predicted EUR using the regression equations agrees with the simulation results very well with a minimum r^2 value of 0.96. Seasonal DER was then calculated from EUR regression equations. These regression functions are recommended for use in ASHRAE Standard 152P to predict energy use and distribution efficiency changes resulting from continuous fan operation.

INTRODUCTION

In order to maintain acceptable indoor air quality, it is essential that fresh outdoor air be brought into the conditioned space. ASHRAE Standard 62 (ASHRAE 2001) provides guidance in determining how much fresh air is needed for residential homes. Since natural infiltration is insufficient to meet the standard (Holton and Beggs 2000), residential ventilation systems are required. These systems are of two main types; independent and attached ventilation. The typical independent system consists of a central exhaust and a heat recovery ventilation system. The central exhaust system is a continuously operated and unbalanced mechanical ventilation system. Makeup air for the exhaust flow occurs through envelope leakage openings. The heat recovery system, however, represents a continuously operated and balanced mechanical ventilation system that has its own supply and exhaust system.

The attached ventilation system is part of the air distribution system that distributes the fresh air into the conditioned space. In general, there are two implementation methods for this type of system. Both methods require an outdoor duct with one end connected to the return side of the distribution system and the other end connected to the outdoors. The first method requires installing a dedicated outdoor fan inside the outdoor duct to bring the forced outdoor air into the conditioned space via the duct system. The outdoor fan runs continuously, while the supply air fan operates simultaneously with a heating or cooling coil that only responds to the thermostat. The second method involves running the supply fan continuously, and outdoor air is drawn by suction into the duct system due to the pressure difference between the two ends of the outdoor duct. The supply fan operation is independent of the cooling and heating equipment operation. This mode of operation is called *continuous fan operation* in this paper.

Five ventilation systems were tested in a house in Pittsburgh (Holton and Beggs 2000). Three of these were the inde-

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pendent type and the remaining two were the attached type. Their paper evaluated thermal performance and ventilation effectiveness of the five systems. However, the impact of air distribution was not discussed in detail for the attached type of system. Similar ventilation systems were also examined (Wray et al. 2000) through building simulations. The study showed that the central exhaust-only system was the best overall mechanical ventilation system option in terms of operating cost, while the forced-air cycler was the worst. Due to the limitation of the model, system interactions were not simulated. The interaction between air distribution system and ventilation system was not addressed.

The primary goal of this paper is to examine the impact of the attached type of ventilation system on building energy use and system performance. Since there is no direct system interaction with the independent type of ventilation system, that system type is not studied here. In general, when fresh air is introduced, additional energy use accrues from equipment and system interactions. The additional energy use in the equipment comes from the outdoor fan power usage to bring fresh air into the conditioned space and condition it as well. However, in mild climates, fresh air can sometimes be used to cool the conditioned space directly, similar to an economizer operation. The additional energy use from system interactions is based on duct system response to the outdoor air. When the supply leaks are larger than the return leaks, building envelope tightness becomes a factor in determining how much mechanically driven infiltration is brought into the conditioned space. Compared to the case without continuous fan operation, introducing fresh air may pressurize the conditioned space. The energy use caused by uncontrolled infiltration due to depressurization without continuous fan operation may be eliminated by introducing outdoor fresh air. When the return leak is dominant, the indoor is more pressurized with continuous fan operation. It is expected that no additional energy is needed from system interactions. Therefore, ventilation directly impacts building energy use.

ASHRAE Standard 152P (ASHRAE 2001) provides calculations to quantify the efficiency of residential forced-air distribution systems. However, it does not address the impact from ventilation systems, such as continuous fan and extended operation, that have interactions with forced-air systems. Ventilation also has an impact on duct system efficiency in addition to energy use. There are two main factors that affect distribution efficiency. First, when the fresh air is introduced, inlet conditions at the cooling coil are changed, which then impact the efficiency of cooling coils. Second, indoor pressure changes due to continuous fan operation can cause distribution efficiency changes, due to the attached airflow regimes. Therefore, ventilation also has a direct impact on distribution efficiency.

This paper presents the impact of continuous fan operation on energy use and air distribution system efficiency through detailed building simulations using the FSEC 3.0 program (FSEC 1992). This is one of the tasks of ASHRAE research project 1165-RP, “Assess Impact of Continuous/Extended Fan Operation on Ventilation Effectiveness and Energy use.” In order to make simulation results useful and practical, regression equations were developed by performing statistical analysis on simulation results to quantify their impact. The criteria were to produce equations in an easily implementable format with a preference for including as few parameters as possible. In addition, all parameters are to be measurable directly from testing. The resulting regression equations are recommended to the SPC-152P committee for use in predicting energy use and distribution efficiency incurred from continuous fan operation.

EXAMINATION OF CONTINUOUS/EXTENDED FAN OPERATION

This paper concentrates on energy use and distribution efficiency changes incurred from introducing necessary outdoor air and system interactions using continuous fan operation. The study using the first method can be found in the final report of ASHRAE Research Project 1165-RP (Gu et al. 2001).

Before discussing results in detail, it is necessary to explain the supplemental definitions used in this paper. Energy use ratio (EUR) is defined as a ratio of the total energy use with the outdoor system to the total energy use without the outdoor system. EUR is a multiplier that is used to predict additional energy use when the outdoor system is incorporated.

$$EUR = \frac{E_{wv}}{E_{nv}} \qquad (1)$$

where

E_{wv} = energy use with an outdoor system

E_{nv} = energy use without an outdoor system

Distribution efficiency with an outdoor system is defined as a ratio of the total energy use, including additional fan energy use with perfect ducts (thus, without energy losses), to that with real ducts. Distribution system efficiency without an outdoor system is defined as a ratio of the total energy use without continuous fan operation with perfect ducts to that with real ducts. In general, distribution system efficiency with the outdoor system is larger than distribution system efficiency without the outdoor system because the total energy use with continuous fan operation with perfect ducts is larger than that without continuous fan operation. The distribution efficiency ratio (DER) is defined as a ratio of distribution efficiency with the outdoor air system to distribution efficiency without the outdoor air system. It is also a multiplier that is used to predict the distribution efficiency with the outdoor system when the distribution efficiency without the outdoor system is known. DER is also represented by EUR with and without the outdoor system:

$$DER = \frac{\eta_{wv}}{\eta_{nv}} = \frac{E_{wv,p}/E_{wv,r}}{E_{nv,p}/E_{nv,r}} = \frac{E_{wv,p}/E_{nv,p}}{E_{wv,r}/E_{nv,r}} = \frac{EUR_p}{EUR_r} \qquad (2)$$

where

η_{wv} = distribution system efficiency with an outdoor system

η_{nv} = distribution system efficiency without an outdoor system

$E_{wv,p}$ = energy use with an outdoor system and perfect ducts

$E_{wv,r}$ = energy use with an outdoor system and real ducts

$E_{nv,p}$ = energy use without an outdoor system and with perfect ducts

$E_{nv,r}$ = energy use without an outdoor system and with real ducts

EUR_p = energy use ratio with perfect ducts

EUR_r = energy use ratio with real ducts

SIMULATION CHARACTERISTICS

In the study of the impact of continuous fan operation and system interactions, the parameters considered included (1) house types, (2) climates, (3) duct system configurations, (4) duct leakage and insulation levels, (5) equipment types, (6) ventilation rates, and (7) envelope leakage. Variations of the first four parameters are the same as those in the previous study (Gu et al. 2003). Duct insulation and leakage levels used in the present study are:

- R-4.2, 6, and 10 (0.74, 1.06, and 1.76 $m^2 \cdot K/W$)
- a) 10% supply and 5% return, b) 10% supply and 10% return, and c) 10% supply and 5% return.
- The percentage used in the leakage levels is compared to the total supply airflow rate.

Equipment Type Parameter

Two types of air conditioners, heat pumps for heating, and gas furnaces are selected. A single-capacity air conditioner with SEER of 10 represents the minimum efficiency available in the market, while a two-speed air conditioner with SEER of 17.6 corresponds to the highest efficiency in the market. Heating efficiencies are HSPF 8.0 for a single-capacity heat pump and HSPF 8.6 for a two-speed heat pump. Both heat pumps have backup electric heaters. These two types of heat pumps represent the typical low and high efficiencies in the market. Heating efficiencies are AFUE 78 for a power combustion gas furnace and AFUE 91 for a condensing gas furnace, corresponding to the low and high efficiency of gas furnaces in the market. Table 1 lists equipment types and associated climates used in the study.

Air Distribution System and Ventilation Rate Parameter

An outdoor duct has been introduced. One end is located outdoors and the other end is connected to the main return duct before the air-handling unit. The air handler is located in a garage, which allows the supply fan to suck the required outdoor air through the outdoor duct and distribute the outdoor air through the air distribution system. The outdoor ventilation rates used in the study are 0, 0.033, and 0.052 m^3/s (0, 70, and 110 CFM). The zero ventilation rate is defined as having no ventilation air introduced, while the supply fan still operates continuously, so that additional infiltration is introduced whether the heating and cooling equipment is on or off. It is worth noting that additional energy caused by the additional infiltration is only accounted for when the coil turns off.

Building Envelope Leakage

Three different levels of envelope leakage are used in the study. The values are 5, 12.7, and 20 ACH50 (air changes per hour at a 50 Pa pressure difference between indoors and outdoors as commonly measured by a blower door). The base building envelope leakage is 12.7 ACH50, which is an average value, determined from the monitoring of 99 existing central Florida homes (Cummings et al. 1991). Values of 5 and 20 ACH50 were used for tight and leaky buildings, respectively. These values were the 10% and 90% values in the building envelope leakage distribution from the same study.

A split duct air distribution system is applied to all of the cases analyzed in this paper. The air distribution system has two identical subsystems. One is located above the ceiling and the other is located below the floor in a crawl space or basement, depending on house foundation type and climate. When the split duct system is applied, the crawl space foundation is

TABLE 1
Cooling and Heating Equipment Types

Equipment Type	Efficiency	Usage	Climate
Single-capacity air conditioner	SEER 10	Cooling	Miami & Baltimore
Two-speed air conditioner	SEER 17.6	Cooling	Miami & Baltimore
Single-capacity heat pump with backup electric heater	HSPF 8.0	Heating	Baltimore & Minneapolis
Two-speed heat pump with backup electric heater	HSPF 8.8	Heating	Baltimore & Minneapolis
Power combustion gas furnace	AFUE 78	Heating	Baltimore & Minneapolis
Condensing gas furnace	AFUE 91	Heating	Baltimore & Minneapolis

TABLE 2
Averaged Energy Uses and Distribution Efficiency Ratios

Operation	Climate	Equipment	110 CFM (52 L/s)		70 CFM (33 L/s)		0 CFM (0 L/s)	
			EURave	STDEV	EURave	STDEV	EURave	STDEV
Cooling	Miami	SEER 10	1.32	0.03	1.28	0.02	1.22	0.03
		SEER 17.6	1.52	0.05	1.48	0.05	1.4	0.06
	Baltimore	SEER 10	1.43	0.07	1.42	0.07	1.4	0.07
		SEER 17.6	1.85	0.13	1.83	0.14	1.78	0.14
Heating	Baltimore	HSPF 8.0	1.73	0.08	1.5	0.07	1.19	0.06
		HSPF 8.8	1.78	0.10	1.53	0.08	1.18	0.06
		AFUE 78	1.67	0.09	1.50	0.03	1.23	0.06
		AFUE 91	1.70	0.08	1.53	0.04	1.28	0.07
	Minneapolis	HSPF 8.0	1.63	0.12	1.39	0.07	1.05	0.02
		HSPF 8.8	1.65	0.13	1.4	0.07	1.04	0.01
		AFUE 78	1.58	0.04	1.40	0.02	1.12	0.04
		AFUE 91	1.60	0.02	1.42	0.02	1.14	0.04

selected for the Miami and Baltimore climates, while the basement foundation is selected for the Minneapolis climate. The slab-on-grade house type is not used with the split duct system. Although the split duct system may not represent physical reality, it is useful as an abstraction for estimating interactions between duct system and equipment to cover impacts on duct systems, both above the ceiling and below the floor.

SIMULATION RESULTS FOR CONTINUOUS SUPPLY FAN OPERATION

Using the above parameters, more than 100 sets of seasonal simulations were performed by varying equipment type, climate, ventilation rate, and building envelope leakage. Each set consists of ten cases, one of which uses perfect ducts (without any leaks and zero conductive energy losses). The remainder use three different levels of duct insulation and three levels of leakage.

Table 2 presents energy use ratios with varying ventilation rates averaged over building envelope leakage, duct insulation, and leakage levels. The first three columns are operating condition, climate, and equipment efficiency, whose corresponding equipment type can be found in Table 1. The next six columns list values of energy use ratio averaged over duct insulation and leakage levels and associated standard deviations in three different ventilation rates. Each average EUR and standard deviation was calculated from 30 seasonal simulations. Since energy use with continuous fan operation is more than that without continuous fan operation, energy use ratios are more than 1.0. The standard deviations range from 0.01 with average EUR of 1.04 to 0.14 with average EUR of 1.83. The relatively small standard deviations show that the averaged EUR may be used to represent all insulation and leakage levels. The minimum average energy use ratio is 1.04 with 0 CFM outdoor air using a two-speed heat pump in Minneapolis. This would indicate a 4% increase in heating energy use in the Minneapolis climate. The maximum average energy use ratio is 1.85 with 110 CFM outdoor air using a two-speed air conditioner in Baltimore. This would indicate an 85% increase in space conditioning energy use in the Baltimore climate. In general, the energy use ratio increases as the ventilation rate and equipment efficiency increase. In the next section, the results obtained from simulations will be used in a regression analysis.

Figures 1 through 3 show seasonal average energy use ratios for Miami, Baltimore, and Minneapolis, respectively. It may be observed that EUR is a linear function of ventilation rate. The difference of EUR with different cooling equipment efficiencies is greater than that with different heating equipment efficiencies.

SIMULATION RESULTS ANALYSIS AND DISCUSSION

The averaged values of energy use and distribution efficiency ratios provided in Table 2 can be used for approximating the impact on energy use. However, the averaged values cannot provide detailed information on how other parameters affect energy use ratios. These include duct system leakage, insulation level, building tightness, ventilation rate, and equipment efficiency. This section quantifies the ratios by performing statistical analysis for real applications. Seasonal simulation results with all the parameters used in the simulations were used as independent variables in the analysis. These parameters are either available from building specification (such as equipment type and efficiency), or measured from testing (such as supply and return leaks and envelope leakage). As long as energy use ratios with perfect and real ducts are

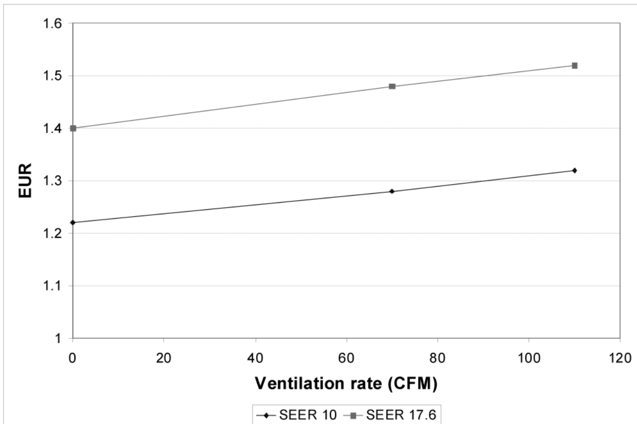

Figure 1 *Cooling seasonal energy use ratio using single- and two-speed air conditioners in Miami.*

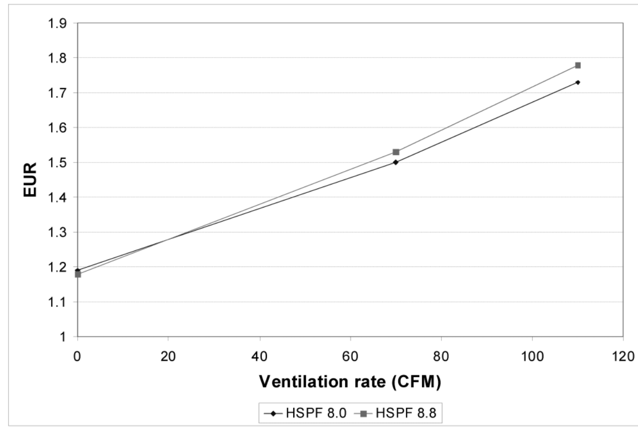

Figure 2 *Heating seasonal energy use ratio using single- and two-speed HPs in Baltimore.*

quantified by the above parameters, distribution efficiency ratios can be calculated using Equation 2. Therefore, two regression equations have to be provided to calculate energy use ratios with perfect and real ducts. The criteria to generate regression equations must not only include the physics, but must also be simple to use. It should be pointed out that the parameters of duct leakage and insulation levels are used to generate regression equation for real ducts only.

Energy Use Ratio

The energy use ratio with perfect ducts may be represented as a linear function of equipment efficiency, building tightness, and outdoor ventilation rate for cooling equipment:

$$EUR_p = a_0 + a_1 * EE + a_2 * OA + a_3 * EL \quad (3)$$

where

EUR_p = energy use ratio with perfect ducts

a_i = constant coefficients (i = 0-3)

EL = envelope leakage [ACH50]

OA = outdoor ventilation rate [cfm or L/s]

EE = cooling equipment efficiency [SEER]

The energy use ratio with real ducts may be represented as a linear function of equipment efficiency, duct insulation and leakage levels, building tightness, and outdoor ventilation rate and as a product of building tightness and ventilation rate for cooling equipment:

$$EUR_r = a_0 + a_1 * EE + a_2 * OA + a_3 * EL + a_4 * SL + a_5 * RL + a_6 * R + a_7 * OA * EL \quad (4)$$

where additional parameters are defined as:

EUR_r = energy use ratio with real ducts

a_i = constant coefficients (i = 0-7)

R = duct insulation level [h.ft^2.°F/Btu or m^2.K/W]

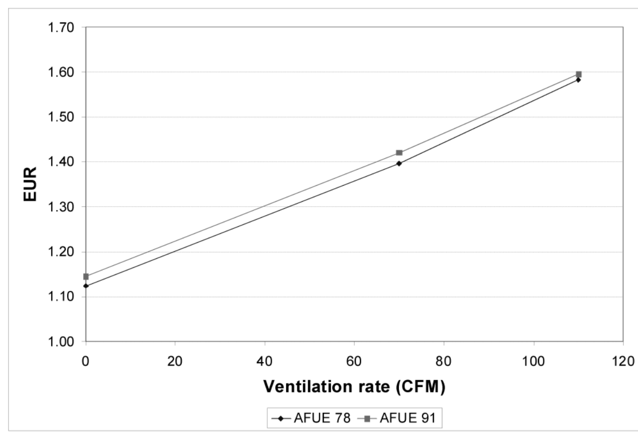

Figure 3 *Heating seasonal energy use ratios using gas furnaces in Minneapolis.*

RL = percentage of return leak compared to the supply fan flow rate [%]

SL = percentage of supply leak compared to the supply fan flow rate [%]

Tables 3 and 4 list coefficients and the associated r^2 of energy use ratio with perfect and real ducts.

The minimum values of r^2 are 0.987 and 0.96 for perfect and real ducts. These indicate that predicted EURs using regression equations agree quite well with the simulation results. The regression equations show that the energy use ratio with perfect ducts is a linear function of equipment efficiency, ventilation rate, and envelope leakage. However, EUR_p increases directly with equipment efficiency and ventilation rate but inversely with envelope leakage. The magnitude of regression coefficients indicates that ventilation rate has a greater impact in Miami than in Baltimore, while envelope leakage has a greater impact in Baltimore than in Miami.

The regression equation with real ducts is a linear function of equipment efficiency, ventilation rate, envelope leakage, duct leakage, and duct insulation levels. In addition, the equation is also a function of a product of ventilation rate and envelope leakage. In general, the energy use ratio with real ducts increases directly with parameters, except for supply leak.

Regression equations of energy use ratio with perfect ducts for heating equipment, including heat pumps and gas furnaces, may be expressed in the following format:

$$EUR_p = a_0 + a_1{*}EE + a_2{*}OA + a_3{*}EL + a_4{*}OA{*}EL{*} \quad (5)$$

where

EE = equipment efficiency (HSPF for heat pumps and AFUE for gas furnaces)

Tables 5 and 6 list coefficients and the associated r^2 of the energy use ratio with perfect and real ducts.

The minimum values of r^2 are 0.97 and 0.96 for perfect and real ducts, respectively. These indicate that the predicted ERUs using regression equations agree quite well with the simulation results. The regression equations show that the energy use ratio with perfect ducts is a linear function of equipment efficiency, ventilation rate, envelope leakage, and a product of ventilation rate and envelope leakage. In general, heating EUR_p increases directly with equipment efficiency and ventilation rate but inversely with the ventilation rate and envelope leakage product. The envelope leakage has negative coefficients in Baltimore, which is consistent with the cooling EUR_p, and positive coefficients in Minneapolis.

Although the regression equations of the heating EUR_r have the same format as the cooling EUR_r, the impacts of parameters are slightly different. One possible reason is that since there is a greater temperature difference between indoors and outdoors in the heating season than that in cooling season, ventilation rate has a greater impact in heating than cooling.

It is worth noting that simple linear curve fits may not represent system interactions very well, although EUR predictions agree quite well with the simulation results. Further work is needed to provide more meaningful predictions. However, the regression equations may be considered a valuable tool in predicting impact of ventilation rates on energy use.

Distribution Efficiency Ratio

Distribution efficiency ratio (DER) is defined as a ratio of EUR with perfect ducts to that with real ducts, as shown in Equation 2, where EUR is predicted using Equations 3-5. Table 7 lists values of r^2 to show comparison between calculated DERs and simulation results. They range from 0.21 to 0.80, indicating that the agreement between the calculated DERs and simulation results is not as good as the EUR predictions. However, the absolute difference between the values of DER obtained from regression and simulation is small. Figures 4 to 9 show comparisons of seasonal DERs between predictions and simulations in three climates and the three equipment types listed in Table 7. Therefore, the calculated values may be used to reasonably predict distribution efficiency changes with and without continuous fan operation.

TABLE 3
Coefficients and Associated r^2 of Cooling EUR_p

SI units:

Cooling	a_0	a_1	a_2	a_3	r^2
Miami	0.992	0.0325	0.00134	–0.00118	0.987
Baltimore	0.837	0.0717	0.000362	–0.00192	0.998

IP units:

Cooling	a_0	a_1	a_2	a_3	r^2
Miami	0.992	0.0325	0.000633	–0.00118	0.987
Baltimore	0.837	0.0717	0.000171	–0.00192	0.998

TABLE 4
Coefficients and Associated r^2 of Cooling EUR_r

SI units:

Cooling	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	r^2
Miami	0.931	0.0245	0.00207	0.00084	–0.00087	0.000355	0.0211	2.78E-06	0.96
Baltimore	0.866	0.0560	0.000834	0.00116	–0.01135	0.001532	0.0371	1.99E-05	0.99

IP units:

Cooling	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	r^2
Miami	0.931	0.0245	0.000974	0.00084	–0.00087	0.000355	0.00373	1.31E-06	0.96
Baltimore	0.866	0.0560	0.000394	0.001158	–0.01135	0.001532	0.00653	9.4E-06	0.99

TABLE 5
Coefficients and Associated r^2 of Heating EUR_p

SI units:

Heating	Type	a_0	a_1	a_2	a_3	a_4	r^2
Baltimore	HP	0.630	0.0884	0.0131	–0.00367	–0.000191	0.97
	Gas	0.915	0.0210	0.0172	–0.00053	–0.000132	0.99
Minneapolis	HP	0.944	0.00359	0.0123	0.00569	–0.000131	0.99
	Gas	0.988	0.00196	0.0101	0.00325	–6.24E-05	0.99

IP units:

Heating	Type	a_0	a_1	a_2	a_3	a_4	r^2
Baltimore	HP	0.630	0.0884	0.00621	–0.00367	–9.03E-05	0.97
	Gas	0.915	0.0210	0.00814	–0.00053	–1.32E-4	0.99
Minneapolis	HP	0.944	0.00359	0.00580	0.00569	–1.31E-4	0.99
	Gas	0.988	0.00196	0.00475	0.00325	–6.24E-05	0.99

TABLE 6
Coefficients and Associated r^2 of Heating EUR_r

SI units:

Heating	Type	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	r^2
Baltimore	HP	1.045	–0.00251	0.0126	–0.00251	–0.0108	4.13E-05	0.0297	–0.000135	0.98
	Gas	0.926	0.00605	0.0120	0.00605	–0.00127	–0.00192	0.03187	–0.000296	0.96
Minneapolis	HP	1.170	0.00101	0.0136	0.00101	–0.0178	–0.00767	0.0309	–0.000207	0.96
	Gas	0.980	–0.00171	–0.00182	–0.00171	0.00307	0.00208	0.00840	–3.75E-05	0.98

IP units:

Heating	Type	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	r^2
Baltimore	HP	1.045	–0.00251	0.00594	–0.00251	–0.0108	4.13E-05	0.00523	–6.36E-05	0.98
	Gas	0.926	0.00605	0.00567	0.00605	–0.00127	–0.00192	0.00561	–0.00014	0.96
Minneapolis	HP	1.170	0.00101	0.006438	0.00101	–0.0178	–0.00767	0.00544	–9.78E-05	0.96
	Gas	0.980	–0.00171	–0.00086	–0.00171	0.00307	0.00208	0.00148	–1.77E-05	0.98

TABLE 7
Values of r^2 of Calculated DER

Location	Equipment	r^2
Miami	AC	0.62
Baltimore	AC	0.80
Baltimore	HP	0.56
	Gas	0.21
Minneapolis	HP	0.53
	Gas	0.43

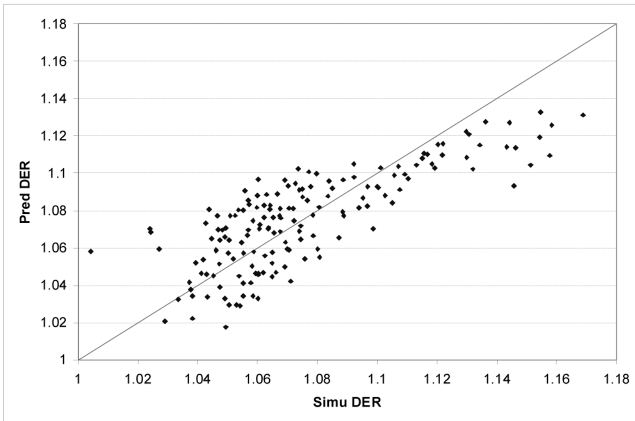

Figure 4 *Comparison of cooling seasonal DER between simulation and prediction in Miami.*

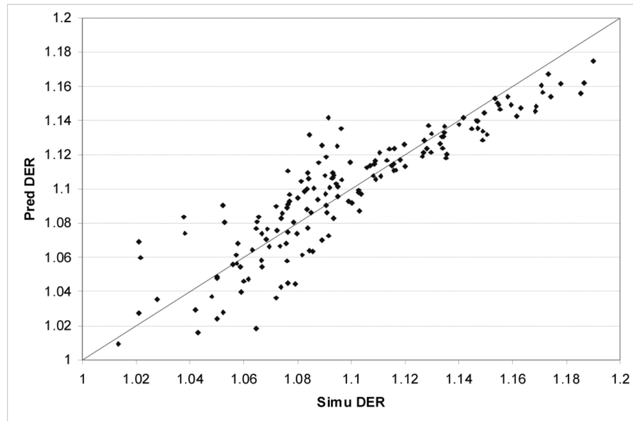

Figure 5 *Comparison of cooling seasonal DER between simulation and prediction in Baltimore.*

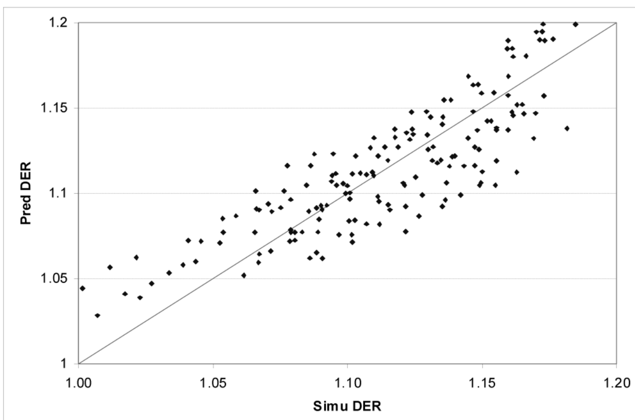

Figure 6 *Comparison of heating seasonal DER between simulation and prediction in Baltimore using heat pumps.*

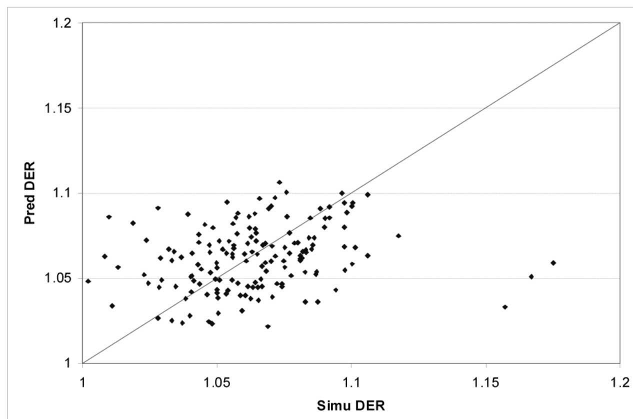

Figure 7 *Comparison of heating seasonal DER between simulation and prediction in Baltimore using gas furnaces.*

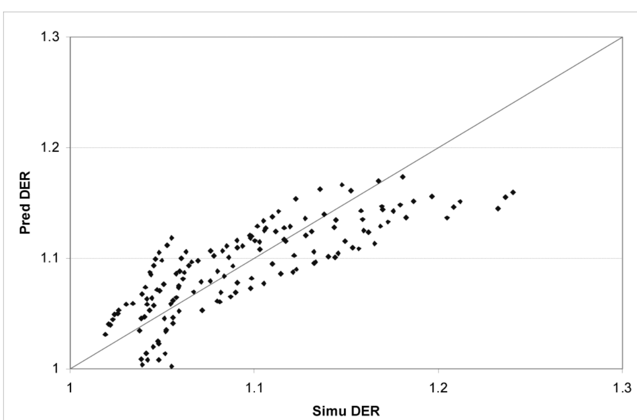

Figure 8 *Comparison of heating seasonal DER between simulation and prediction in Minneapolis using heat pumps.*

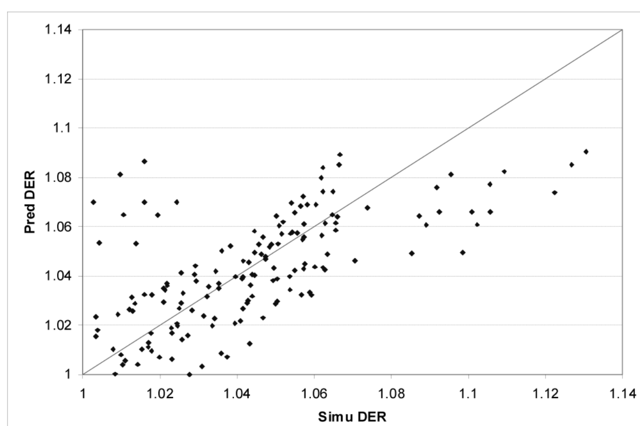

Figure 9 *Comparison of heating seasonal DER between simulation and prediction in Minneapolis using gas furnaces.*

Equipment Sizing

It is worth noting that a fixed equipment size was used in the present study. The equipment capacity was determined from the peak loads. Since the equipment operates at part load most times, equipment capacity plays an important role in determining fan energy use during equipment off time.

CONCLUSIONS AND RECOMMENDATIONS

- Energy use and distribution efficiency ratios are multipliers that can be used to predict the impact of continuous fan operation when energy use and distribution efficiency without continuous fan operation are known. Averaged values of energy use and distribution efficiency ratios are useful in approximating the impact on energy use and system efficiency.
- Results of the present work show that the seasonal cooling and heating energy use ratios are a linear function of equipment efficiency, ventilation rate, and envelope tightness. In addition, a product of envelope tightness and ventilation rate was introduced to enhance regression of heating EUR_p and heating and cooling EUR_r. The predicted EUR agrees well with simulation results. The minimum r^2 is 0.96. This appears to be a better approach to predicting energy use with the outdoor air system and was recommended for inclusion in ASHRAE Standard 152P for continuous fan operation applications.
- Seasonal distribution efficiency may be calculated from seasonal energy ratios with perfect and real ducts. However, DER predictions do not compare as well as with EUR predictions. Since DER is relatively smaller than EUR, the absolute difference is small. Therefore, the predicted DER still can be used with some confidence.
- In general, average energy use ratios vary from 1.27 to 1.81 across climates and equipment types. It is worth noting that ventilation rates increase cooling and heating by 22% to 85%.

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