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Modeling the thermal distribution efficiency of ducts: comparisons to measured results

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Abstract

This paper presents a comparison of predictions from a duct efficiency model developed by the authors with measured real-time heating system efficiency measurements from six site-built residential homes with natural gas furnaces in the Puget Sound region. The model takes into account the interaction between supply and return side losses, the interaction between conduction and air leakage losses, the interaction between unbalanced leakage and natural infiltration, and the recovery of heat through the building envelope from ducts in various locations within the home. It does not take into account losses due to cycling. Field testing was done using a short-term coheating methodology. Both the modeling and tests were done before and after aggressive duct air leakage sealing and insulation retrofits.

Keywords: Air duct; Heating system; Natural gas furnace; Air leakage

1. Introduction

In recent years thermal losses in the duct work of forced-air distribution systems have come under intense scrutiny. In forced-air distribution systems, which are common in the United States, air is drawn through return duct work by a blower fan, heated or cooled (as appropriate) by such components as electric resistance elements, burning natural gas or oil, or a compressor, and then delivered to the house via supply ducts. The blower fan is typically located just upstream of the heating or cooling components. In an ideal situation, all of the return air is taken from the house through return grilles and all of the supply air is delivered to the house through supply registers. The periods when the conditioning system operates is controlled by a thermostat to maintain the desired temperature in the home.

Losses in the duct work are due mainly to air leaks and conduction losses. Several studies have quantified the magnitude of these losses in small samples of buildings around the United States [1–5]. Modera [6] gave an overview of the impacts of duct system leakage on both infiltration and thermal loads.

Olson et al. [7] found that 22 homes with at least 50% of the ducts in unconditioned spaces averaged about a 29% efficiency loss due to leakage and conduction losses, compared to about 2% efficiency loss in two homes with all interior ducts. Air sealing retrofits on six of these homes [8], which were selected to have a large amount of leakage to outside, resulted in an improvement of the efficiency of about 16%, with a reduction of efficiency losses of about 44%. Leakage to outside was reduced by about 70%.

Jump et al. [9] found that sealing and insulating duct systems in 24 Sacramento, CA homes resulted in an average reduction of energy consumption of about 18%.

Siegel et al. [10] found that performing aggressive air sealing retrofits on eight manufactured homes with at least 250 cfm duct leakage to outside resulted in an energy savings of about 16% and a reduction in leakage of about 80%.

However, until recently there had been no simple mathematical model for estimating the thermal efficiency of forced-air distribution systems that includes the interaction between supply and return sides, the interaction between conduction losses and air leakage losses, the interaction between unbalanced leakage and natural infiltration, and regain, which is the energy that is lost by the ducts but recovered to the conditioned space as useful conditioning energy. A model of this type is desirable so that the efficiency of a system can be estimated based on a few simple measurements and so that it can be applied to a large number of homes by contractors, utilities, researchers, etc. One of the primary uses of such a

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model is to predict the change in energy use if various options, such as additional insulation or air sealing, are performed.

A simple model has been developed by Palmiter and Francisco [11] which accounts for the complex interactions mentioned above and also allows for different supply- and return-side zone temperatures. A similar model has been proposed for use in the draft version of ASHRAE Standard 152P [12]. A sensitivity analysis on the model in Ref. [11] shows that supply losses have a greater impact on the overall efficiency than do return losses of the same type (conduction or leakage) and magnitude, and that conduction losses have a greater impact than do leakage losses of the same size. It must be kept in mind that the model in its present form does not account for latent loads, which can be important in cooling situations. For sensible loads, and assuming no conduction losses, the sensitivity analysis shows that the temperature in the space in which the return ducts are located must be greater than the sum of the outdoor temperature and the temperature change across the equipment for the return leakage to be of greater importance than the same amount of supply leakage. In many parts of the United States, particularly the Southwestern desert, latent loads are small and the preceding criterion may be used as a rough estimate of whether supply or return leakage is more important.

This paper presents the results of applying the Palmiter and Francisco model to six site-built, gas-heated homes in the Puget Sound region and compares these results to measured efficiency data. These results are based on a detailed set of measurements which are found in Davis et al. [13].

2. The duct model

2.1. Fundamentals

Fig. 1 shows a simplified duct system, with leaks assumed to be at the registers and ducts assumed to be all in unconditioned spaces, such as crawl spaces, garages, and attics. In this figure, T_{sr} and T_{rr} are the supply and return temperatures at the registers, T_{sp} and T_{rp} are the supply and return plenum temperatures, T_{as} and T_{ar} are the ambient temperatures around the supply and return ducts, T_m is the mixed temperature of the air in the return duct after the return leak, T_{ai} is the temperature of the natural infiltration air from outdoors, ΔT_e is the temperature rise across the equipment, q_e is the energy produced by the equipment, and m_e is the mass flow rate of air through the equipment. The two primary mechanisms for heat loss from ducts are conduction and leakage.

From standard heat-exchanger theory for steady-state flow through a pipe with a constant ambient temperature, the conduction efficiency β can be defined as

$$\beta=\frac{T_{out}-T_a}{T_{in}-T_a}=\exp\left(-\frac{UA}{mC_p}\right) \tag{1}$$

where T_{out} is the temperature at the outlet of the pipe; T_{in} is the temperature at the inlet of the pipe; T_a is the ambient temperature around the pipe; U is the heat transfer coefficient; A is the duct surface area; m is the mass flow rate of the air in the pipe; C_p is the specific heat of air.

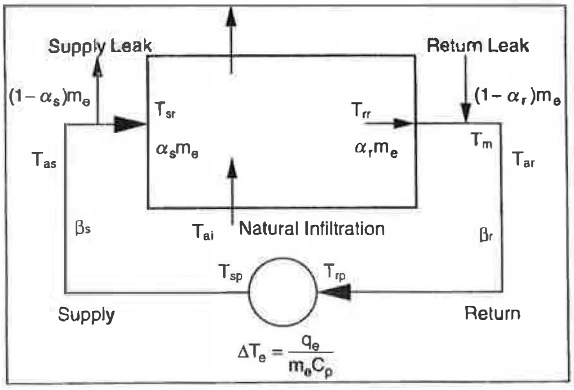

Fig. 1. Simplified schematic of duct losses.

For air leakage efficiency, assume that the percentage loss is constant and is concentrated at one place along the pipe. The air leakage efficiency α can be defined as

$$\alpha=\frac{m_{out}}{m_{in}}=1-\text{Leak fraction} \tag{2}$$

where m_{out} is the outlet mass flow rate from the pipe; m_{in} is the inlet mass flow rate from the pipe; Leak fraction is the ratio of the leakage to outdoors to the total flow rate produced by the air handler.

2.2. Delivery efficiency

Using these definitions, the delivery efficiency η_0, which is defined as the fraction of energy provided by the equipment that actually gets delivered through the building envelope by the duct work during steady-state conditions, can be expressed as

$$\eta_0=\alpha_s\beta_s-\alpha_s\beta_s(1-\alpha_r\beta_r)\frac{\Delta T_r}{\Delta T_e}-\alpha_s(1-\beta_s)\frac{\Delta T_s}{\Delta T_e} \tag{3}$$

where ΔT_r is the temperature difference between the return register and the air around the return duct; ΔT_s is the temperature difference between the return register and the air around the supply duct; ΔT_e is the temperature change across the conditioning equipment.

In these definitions the return register temperature is identified with the house temperature. This expression of the delivery efficiency has the properties that each term is dimensionless and that the supply and return temperature differences are separated and linear. In addition, the only temperature measurements required are those at the return register and in the zones where the supply and return ducts are located. Eq. (3) is identical to that found in Standard 152P for delivery effectiveness, which has the same definition as delivery efficiency. For a detailed derivation of this equation, see Ref. [11]. Note that this definition of delivery efficiency differs from that found in ASHRAE [14], which says that the delivery efficiency is the ratio of the energy delivered through the registers, not through the building envelope, to the equipment output capacity.

There are several important implications of Eq. (3). One is that the delivery efficiency can be no better than the product of the supply-side leakage and conduction efficiencies, regardless of the temperature differences. Another is that if the return-side ambient temperature is the same as the temperature at the return register the return duct has no impact on the delivery efficiency, no matter how large the leakage. Further, as the temperature change across the equipment decreases the delivery efficiency also decreases. This raises concern about heat pumps, which tend to have much smaller temperature changes than do other types of equipment such as furnaces. Eq. (3) also suggests that, if all else is held constant, a decrease in equipment capacity or an increase in air handler flow rate will result in a reduction of the delivery efficiency.

The model as described above assumes that all of the leaks are at the envelope end of the ducts. However, it can be extended to the situation where a fraction ϕ of the leakage is at the plenum end of the duct. Eqs. (2) and (3) are the same, but the equation for the conduction efficiency is modified as follows:

$$\beta=\exp\left(-\frac{UA}{(\phi+(1-\phi)\alpha)mC_p}\right) \quad (4)$$

Unless both conduction losses and leakage are large, the difference between assuming all of the leaks are at the envelope and assuming all of the leaks are at the plenum will be small, typically less than one or two percentage points in the efficiency.

2.3. Distribution efficiency

While the delivery efficiency is an important measure of efficiency, in large part because it indicates the fraction of energy supplied by the equipment that is delivered via the intended paths, it usually does not represent the fraction of the supplied energy that actually goes to satisfying the load of the house. The fraction of supplied energy that is delivered to the house as useful heat is called the distribution efficiency. Two primary factors which result in a distribution efficiency different from the delivery efficiency are the interaction of unbalanced duct leakage with natural infiltration, and the effect of regain. Regain is energy that is lost by the ducts to unconditioned spaces but is recovered as useful energy by the building. Some of the primary mechanisms through which regain occurs are conduction through the envelope, air leakage directly from ducts to the conditioned space, and the reduction in loss from the conditioned space to the buffer space due to an increase (or, in the case of cooling, a decrease) of buffer space temperature resulting from the duct losses.

Delivery efficiency and distribution efficiency only include the effects of ducts on the heat required of the equipment by the house. Neither efficiency measure includes the efficiency of the equipment itself, such as the combustion efficiency of a gas furnace or the compressor efficiency of an air-conditioner or heat pump.

2.3.1. The interaction of unbalanced duct leakage with natural infiltration

The effect of the interaction of unbalanced duct leakage with natural infiltration is to change the load of the building. If the return leakage is greater than the supply leakage, the building is pressurized. This results in less air from outdoors entering the building (up to the point where no outdoor air is entering the building), reducing the amount of energy the equipment must provide. If the supply leakage is greater than the return leakage, the reverse is true.

Since the effect of this interaction is a change in building load rather than a change in the thermal performance of the ducts themselves, it is represented as a subtracted offset in the efficiency instead of a multiplier. The offset, $\eta_{\rm in}$, which is incorporated in the model as the loss due to the interaction with natural infiltration, can be estimated using the fan model developed by Palmiter and Bond [15–17] and incorporated by ASHRAE [14]. The offset has the property that, in the case of return-dominated leakage ($\alpha_s > \alpha_r$), the distribution efficiency increases with increasing return leakage compared to ignoring the infiltration interaction term. In extreme cases, such as a return leak in a hot garage in a heating season situation, this increase can offset all of the other losses, resulting in a distribution efficiency greater than 1. Similarly, if the leakage is sufficiently supply-dominated, the additional infiltration can create a higher load that the equipment is unable to meet and the distribution efficiency can be less than 0.

There are two cases to consider: small unbalanced leakage, where the unbalanced leakage is less than or equal to twice the ratio of natural infiltration to equipment flow rate, and large unbalanced leakage, where the unbalanced leakage is greater than twice the natural infiltration rate. Note that infiltration should only include air that comes through the building envelope, not through holes in the duct work.

2.3.1.1. Small unbalanced leakage

Let $m_{\rm nat}$ be the mass flow rate of the natural infiltration when the conditioning equipment is off, ΔT be the temperature difference between the house and outdoors, and η_t be the delivery efficiency minus the infiltration interaction offset (which can also be thought of as the distribution efficiency if all ducts are outside so that there is no regain). If

$$\frac{1}{2}(\alpha_r-\alpha_s)\leq\frac{m_{\rm nat}}{m_e} \quad (5)$$

then

$$\eta_{\rm in}=\frac{1}{2}(\alpha_r-\alpha_s)\frac{\Delta T}{\Delta T_e} \quad (6)$$

and

$$\eta_1=\alpha_s\beta_s-\alpha_s\beta_s(1-\alpha_r\beta_r)\frac{\Delta T_r}{\Delta T_e}-\alpha_s(1-\beta_s)\frac{\Delta T_s}{\Delta T_e}-\frac{1}{2}(\alpha_r-\alpha_s)\frac{\Delta T}{\Delta T_e} \quad (7)$$

2.3.1.2. *Large unbalanced leakage*

If

$$\frac{1}{2}(\alpha_{\max}-\alpha_{\min})>\frac{m_{\text{nat}}}{m_e},\quad \alpha_{\max}=\max(\alpha_s,\alpha_r),\quad \alpha_{\min}=\min(\alpha_s,\alpha_r) \quad (8)$$

then

$$\eta_{\text{in}}=\left[\alpha_{\max}-\alpha_s-\frac{m_{\text{nat}}}{m_e}\right]\frac{\Delta T}{\Delta T_e} \quad (9)$$

and

$$\eta_1=\alpha_s\beta_s-\alpha_s\beta_s(1-\alpha_r\beta_r)\frac{\Delta T_r}{\Delta T_e}-\alpha_s(1-\beta_s)\frac{\Delta T_s}{\Delta T_e}-\left[\alpha_{\max}-\alpha_s-\frac{m_{\text{nat}}}{m_e}\right]\frac{\Delta T}{\Delta T_e} \quad (10)$$

2.3.2. *Regain*

The amount of duct losses recovered to the conditioned space through regain varies greatly depending on the physical nature of the unconditioned space in which the losses occur. For example, more lost heat will be recovered from a crawl space with no insulation under the building floor compared to that from an identical crawl space under a well-insulated building floor. The regain factor f can be expressed as

$$f=\frac{(\text{UA})_h}{(\text{UA})_h+(\text{UA})_{\text{out}}} \quad (11)$$

where $(\text{UA})_h$ is the conductance from the buffer space to the house (or other conditioned space); $(\text{UA})_{\text{out}}$ is the conductance from the buffer space to outside the house, including to the ground, ambient, and via infiltration through the buffer space.

These conductances should be determined based on the time when the equipment runs, including any interaction between unbalanced duct leakage and the infiltration through the buffer space. See Ref. [11] for a detailed description of how to calculate these conductances, as well as for how to calculate the buffer space temperature if a measured value is not available.

Because the regain applies to the fraction of energy lost to the buffer spaces, it is represented as a multiplier to this loss. However, efficiency losses due to return-side leakage are not energy losses to the buffer space. To determine how to incorporate the regain factor into the model, an expression for the energy lost to the buffer space is needed. On the supply side, the energy lost to the buffer space, q_{LS}, is

$$q_{\text{LS}}=[(1-\alpha_s\beta_s)(\Delta T_e-(1-\alpha_r\beta_r)\Delta T_r)+\alpha_s(1-\beta_s)\Delta T_s]m_eC_p \quad (12)$$

and on the return side, the energy lost to the buffer space, q_{LR}, is

$$q_{\text{LR}}=(1-\beta_r)\Delta T_r m_e C_p \quad (13)$$

If the supply and return ducts are all in the same buffer space, as is assumed in the derivation found in Ref. [11], then the distribution efficiency can be expressed as

$$\eta=\eta_0+f\left(1-\eta_0-\beta_r(1-\alpha_r)\frac{\Delta T_r}{\Delta T_e}\right)-\eta_{\text{in}} \quad (14)$$

If, however, the supply and return ducts are located in different zones, separate supply and return regain factors are required. By calculating supply and return regain factors f_s and f_r, respectively, and applying them to the corresponding losses q_{LS} and q_{LR}, the distribution efficiency can be written as

$$\eta=\eta_0+f_s\left(1-\eta_0+\left(\frac{f_r}{f_s}-1-\beta_r\left(\frac{f_r}{f_s}-\alpha_r\right)\right)\frac{\Delta T_r}{\Delta T_e}\right)-\eta_{\text{in}} \quad (15)$$

3. Field measurements

3.1. *Overview*

In the winter of 1997 Ecotope was hired by a local utility to do a set of short-term coheat tests on eight site-built homes with gas furnaces. Each of these homes was to be tested before and after aggressive retrofits during which air sealing and, in some cases, insulating of ducts was performed. These houses were selected as potential candidates from a phone interview, which screened for such things as the presence of a basement, sealed combustion furnaces, and houses that were deemed to be too large for effective instrumentation. After the phone interview, an initial set of leakage tests was performed on each house, along with an assessment of the ease of performing both the coheat tests and the retrofit. Based on the analysis of these initial tests, homes with the largest ratio of duct leakage to outdoors on the supply side to the air handler flow were chosen to receive the coheat testing and retrofits. Homeowners were required to leave their homes for two nights while the testing took place to minimize complications from internal gains or other unintended occurrences. The full detailed summary of this project can be found in Ref. [13].

At two of the homes, designated Sites 2 and 3 in the study, damage to the thermostat used to control the furnace resulted in the coheat test results being questionable; these homes are excluded from comparisons in this paper. Table 1 provides some of the pertinent characteristics of the remaining six homes. Only supply duct information is given since supply losses have a much greater impact on the efficiency than do comparably sized return losses.

Table 2
Measured efficiency results

Site	Combustion efficiency (%)	Pre-retrofit efficiency (%)		Post-retrofit efficiency (%)		Savings (%)
		System	Distribution	System	Distribution	
1	77.6	47.9	60.9	55.9	70.6	13.7
4	76.5	53.6	69.0	59.7	77.1	10.5
5	70.0	46.9	66.0	55.1	77.3	14.6
6	76.0	46.6	60.2	61.3	78.5	23.3
7	76.5	50.7	65.4	68.0	87.3	25.1
8	76.0	51.1	66.5	56.7	73.4	9.4
Average	75.4	49.5	64.7	59.4	77.4	16.1

4.2. Measured results from additional on-site tests

The first two columns of Table 3 show results from blower door envelope leakage tests with registers sealed, including m^3/s at 50 Pa depressurization and air changes per hour (ACH) at 50 Pa depressurization. The air change rate is the air flow rate normalized by house volume, which allows for increased comparability of results across homes. Since sealing the registers largely isolates the ducts from the home, the same values were used both pre- and post-retrofit to describe building air-tightness. Envelope leakage data are important to the duct efficiency model because with an appropriate infiltration model they can be used to predict natural infiltration.

There are three measures of duct leakage that are pertinent to the model. The first, total supply duct leakage, which includes leakage to inside, can be combined with flow hood register flow measurements to provide an estimate of air handler flow. The other two pertinent duct leakage measures are the supply and return duct leakages to outside, which are used with the air handler flow to estimate the leakage efficiencies α_s and α_r in the duct efficiency model. Leakage at 50 Pa duct pressurization is shown both pre- and post-retrofit for these three duct leakage measures in the third through eighth columns of Table 3.

The duct leakage under operating conditions depends on the static pressures that exist in the ducts at the leakage locations. It is therefore necessary to make measurements of static

Table 3
House and duct leakage at 50 Pa

Site	House leakage		Total supply duct		Supply duct to outside		Return duct to outside	
	Q_{50} (m^3/s)	ACH_{50}	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
			Q_{50} (m^3/s)	Q_{50} (m^3/s)	Q_{50} (m^3/s)	Q_{50} (m^3/s)	Q_{50} (m^3/s)	Q_{50} (m^3/s)
1	1.65	10.0	0.219	0.144	0.178	0.104	0.115	0.057
4	1.89	22.5	0.226	0.125	0.194	0.084	0.325	0.037
5	1.13	13.3	0.227	0.105	0.152	0.042	0.132	0.030
6	1.19	11.1	0.289	0.057	0.274	0.045	0.046	0.020
7	1.09	9.4	0.188	0.021	0.168	0.013	0.250	0.154
8	1.34	15.6	0.207	0.099	0.108	0.070	0.212	0.038
Average	1.38	13.7	0.226	0.092	0.179	0.060	0.180	0.056

Table 4
Distribution system pressures

Site	Pre-retrofit static pressures (Pa)					Post-retrofit static pressures (Pa)				
	Plenums		Registers	System		Plenums		Registers	System	
	Supply	Return	Average	Supply	Return	Supply	Return	Average	Supply	Return
1	66.5	76.0	4.2	10.6	10.6	73.2	80.2	4.1	13.5	13.5
4	40.3	27.6	3.9	7.8	10.6	44.0	44.0	8.3	8.4	11.7
5	21.6	38.9	1.7	11.7	20.6	24.3	41.1	1.9	13.1	20.6
6	70.0	56.0	5.0	13.7	12.0	79.2	58.8	10.4	15.0	13.0
7	66.0	87.0	9.8	18.6	15.0	68.8	70.9	9.6	17.6	15.0
8	26.5	57.0	4.1	11.2	7.0	26.8	58.4	5.3	20.3	29.0
Average	48.5	57.1	4.8	12.3	12.6	52.7	58.9	6.6	14.6	17.1

Table 5
Distribution system flows at operating conditions

Site	Pre-retrofit flows (m^3/s)					Post-retrofit flows (m^3/s)				
	Leakage to out		Total leakage	Register	Air handler	Leakage to out		Total leakage	Register	Air handler
	Supply	Return	Supply	Supply		Supply	Return	Supply	Supply	
1	0.074	0.041	0.092	0.392	0.484	0.041	0.025	0.063	0.421	0.484
4	0.072	0.169	0.082	0.246	0.328	0.033	0.010	0.045	0.283	0.328
5	0.060	0.080	0.083	0.256	0.338	0.017	0.018	0.047	0.286	0.332
6	0.134	0.020	0.138	0.343	0.481	0.021	0.009	0.027	0.454	0.481
7	0.097	0.131	0.109	0.449	0.558	0.009	0.077	0.009	0.510	0.519
8	0.079	0.074	0.079	0.298	0.378	0.041	0.027	0.055	0.322	0.378
Average	0.086	0.086	0.097	0.331	0.428	0.027	0.028	0.041	0.379	0.420

pressures in the duct system and use engineering judgment to estimate an 'average' static pressure experienced by the leaks. Table 4 shows the pressures in the return and supply plenums, the average static pressure at the supply registers, and the duct system pressure that was used for the estimate of the actual leakage. All static pressures were measured using a pitot tube pointed upstream.

Using the preceding information, total leakage and leakage to outdoors at operating conditions can be calculated, and by incorporating the sum of the supply register flows the air handler flow can be calculated as well. The results are shown in Table 5.

Table 6 shows the temperature differences that are required for the model: from the house to the supply zone (ΔT_s), from the house to the return zone (ΔT_r), from the house to outside (ΔT), and the temperature rise across the equipment (ΔT_e). In cases where supply and/or return ducts ran through more than one space (e.g., in the crawl space, in outside wall cavities, and between floors) the temperature difference is based on an effective duct zone temperature that is calculated as the duct surface area-weighted zone temperature. Temperatures are averages from the furnace cycling periods used in calculating the efficiencies in Table 2.

4.3. Modeled results

The primary emphasis of the modeling effort was to obtain estimates of the distribution efficiency for each case. However, since estimating the delivery efficiency is essentially an intermediate step, these were also recorded. Besides the temperature differences of Table 6, the only parameters required for this efficiency measure are the leakage efficiencies α_s and α_r and the conduction efficiencies β_s and β_r. Since the conduction efficiencies depend on the flow through the ducts, it matters where the leaks are located. Therefore, similar to estimating the average system static pressure seen by the leaks, it is necessary to use engineering judgment to estimate the average flow through the ducts. This was done by assuming a fraction of the leakage was at the air handler and the remainder was at the registers, and then using Eq. (4). The fraction of leakage at the inlet to the ducts was never assumed to be more than 50%, and the impact of the assumptions on conduction efficiencies was only greater than 1.5 percentage points in one case relative to assuming that all of the flow went through the ducts. In this one case, in which the pre-retrofit return conduction loss at Site 4 assumed that half of the leakage was at the inlet, the difference relative to assuming that all of the flow went through the ducts was about four percentage points. Table 7 shows the supply and return leakage and conduction efficiencies, as well as the modeled delivery efficiency η_0 during cycling, both pre- and post-retrofit.

In three of the six houses discussed in this paper, a sufficient number of supply register temperature measurements were taken to also get a measured delivery efficiency during the steady-state test. Since the temperatures during the steady-state test are different from those during cycling, a modeled steady-state delivery efficiency was calculated at each of these three sites for comparability with the measured data.

Table 6
Pertinent temperature differences

Site	Pre-retrofit temperature differences (°C)				Post-retrofit temperature differences (°C)			
	ΔT_s	ΔT_r	ΔT	ΔT_e	ΔT_s	ΔT_r	ΔT	ΔT_e
1	4.78	5.77	19.11	27.70	7.36	6.28	16.74	27.47
4	7.78	8.78	13.95	38.01	10.52	10.52	16.80	38.43
5	12.10	12.10	22.98	28.09	12.88	12.88	23.76	28.69
6	6.20	14.46	14.29	28.50	14.05	16.95	14.04	28.44
7	7.74	5.08	17.26	41.46	7.16	5.59	15.63	44.08
8	12.94	14.59	17.82	36.67	12.47	12.41	15.64	36.39
Average	8.59	10.13	17.57	33.40	10.74	10.77	17.10	33.92

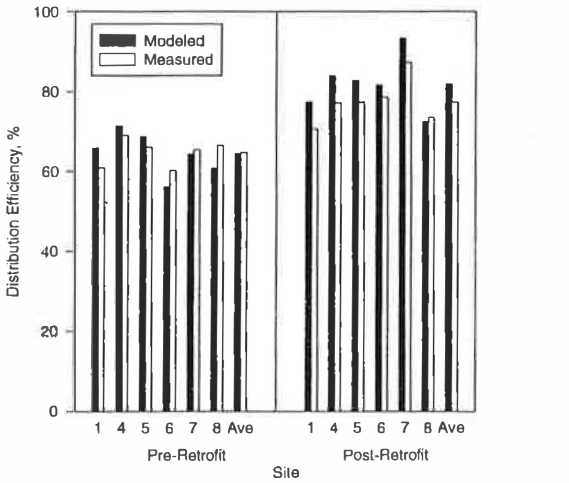

Fig. 2. Comparison of modeled and measured distribution efficiency estimates.

Table 9 shows the estimated regain factors f_s and f_r and the term quantifying the interaction of unbalanced leakage with natural infiltration η_{in}. The relatively high regain factors for Site 4 is due to the floor being uninsulated. The negative infiltration interaction terms indicate return-dominated leakage, and increase the efficiency compared to ignoring the terms.

At Sites 4 and 5, where the supply and return regain factors are the same, Eq. (14) can be used to calculate the modeled distribution efficiency. For the remainder of the homes, Eq. (15) must be used. Fig. 2 and the first two sections of Table 10 compare the modeled distribution efficiency results to the measured results of Table 2. However, in many cases such as utility retrofit programs, it is the energy savings which is the most important result. As such, it is important to investigate not only how well the model predicts the efficiency, but also how well it predicts the change due to incorporating changes or improvements to the duct system. Fig. 3 and the final section of Table 10 compares modeled and measured energy savings as calculated with Eq. (16).

This table shows that all of the pre-retrofit comparisons of modeled to measured distribution efficiency are within six percentage points, with an average discrepancy of 0.2 percentage point. In the post-retrofit cases, all of the comparisons are within seven percentage points with an average difference of 4.5 percentage points. The most likely sources of discrepancy are: (1) the possibility that the air handler flow was not estimated accurately; (2) the possibility that the regain factor was not estimated accurately; (3) the possibility that the average static pressure at the leaks in the ducts was not accurate, resulting in an inaccurate prediction of the duct leakage at operating conditions; and (4) the fact that cycling losses are not included in the modeled efficiency.

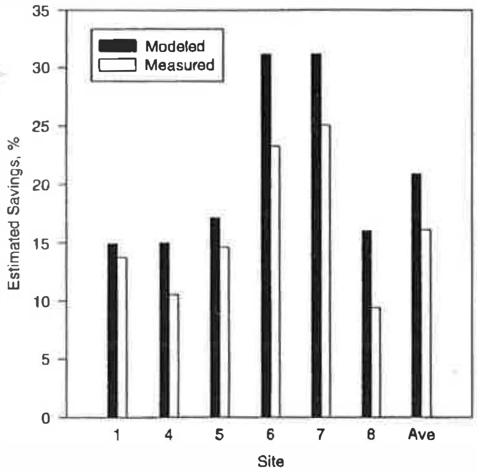

Fig. 3. Comparison of modeled and measured predictions of savings.

Regarding the second item, it can be very difficult to get an accurate regain estimate. One reason is that there can be complex interactions between the different components, such as crawl space walls, ground, and outdoors. For example, when there is leakage into a crawl space, the crawl space is pressurized, and air infiltration through the crawl space from outdoors is reduced. Also, the heat loss to the ground, especially where the crawl space floor meets the walls, is a three-dimensional heat transfer problem; in the modeling a simplified estimate of the effective heat transfer rate to the ground was used.

Another reason why regain factors may be inaccurately estimated is due to the nature of the estimation. Since the predictions depend on visual inspection and evaluation, unseen features can result in an error. For example, one of the most important details in these houses is the amount of

Table 10
Modeled vs. measured distribution efficiency

Site	Pre-retrofit η (%)			Post-retrofit η (%)			Savings (%)		
	Modeled	Measured	Difference	Modeled	Measured	Difference	Modeled	Measured	Difference
1	65.8	60.9	4.9	77.3	70.6	6.7	14.9	13.7	1.2
4	71.3	69.0	2.3	83.9	77.1	6.8	15.0	10.5	4.5
5	68.6	66.0	2.6	82.8	77.3	5.5	17.1	14.6	2.5
6	56.1	60.2	−4.1	81.6	78.5	3.1	31.2	23.3	7.9
7	64.3	65.4	−1.1	93.4	87.3	6.1	31.2	25.1	6.1
8	60.8	66.5	−5.7	72.4	73.4	−1.0	16.0	9.4	6.6
Average	64.5	64.7	−0.2	81.9	77.4	4.5	20.9	16.1	4.8

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