Modeled vs. Measured Duct Distribution Efficiency in Six Forced-Air Gas-Heated Homes

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ABSTRACT

Distribution efficiency was measured using a short-term coheating technique before and after aggressive air sealing retrofits in six Pacific Northwest homes heated with gas furnaces. These houses were selected to have a large amount of air lost from the supply side of the duct system to outdoors. Additional measurements included duct and house leakage, distribution system pressures, and temperatures inside and outside the home as well as in the buffer spaces where the ducts were located. Physical characteristics of the ducts and buffer spaces, including surface area and insulation levels, were also measured. These additional measurements provide the inputs to a duct efficiency model developed by Ecotope, which accounts separately for supply- and return-side losses and for conduction and leakage losses. The model also accounts for duct losses recovered to the house via regain and the interaction of duct leakage with natural infiltration.

This paper presents the measured results of the coheating tests and compares them to the predictions provided by the model. Estimates of the reduction in energy use caused by the retrofits are also calculated from both the coheating measurements and the model.

Introduction

In recent years thermal losses in duct work have come under intense scrutiny. These losses are due mainly to air leaks and conduction losses. Several studies have quantified the savings resulting from duct retrofits in small samples of buildings around the United States (Palmiter, Olson & Francisco 1995; Jump, Walker & Modera 1996; Siegel et al. 1997).

However, field measurement of duct efficiency is typically costly, time-consuming, and provides only a small sample of buildings. As a result, an effort has been made to develop a 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. For such a model to be useful, it should enable the efficiency of a system to be estimated from a few simple measurements and should be usable by contractors, utilities, researchers, etc. in a large number of homes. One of the primary uses of such a model is to predict the change in energy use if various options, such as additional insulation or air sealing, are performed.

A simple model was developed by Palmiter and Francisco (1997) which accounts for the complex interactions mentioned above and also allows for different supply- and return-side zone temperatures. An extension of this model to account for different supply- and return-side regain factors is provided by Davis et al. (1998). A sensitivity analysis on this model shows that supply losses have a greater impact on the overall efficiency than do return losses of the same type (conduction or leakage) and percentage (e.g. 10% supply conduction loss vs. 10% return conduction loss), and that conduction losses have a greater impact than do leakage losses of the same size. The relative impact of similar return losses is greater for cooling than for heating, and in a few situations can even be more important than the supply losses. A similar model has been proposed for use in the draft version of ASHRAE Standard 152P (ASHRAE 1997).

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. (1998).

The Duct Model

There are two standard measures of duct efficiency. The first is the delivery efficiency, which is the fraction of energy provided by the equipment that actually gets delivered across the building envelope by the ducts during steady-state conditions. The second is the distribution efficiency, which takes into account thermal regain and the interaction of duct leakage with natural infiltration. Note that both of these efficiency measures only account for the impacts of the ducts on the energy consumption to condition the house; any equipment efficiency, such as the combustion efficiency of a gas furnace or the compressor efficiency of an air conditioner, is not included.

Delivery Efficiency

The delivery efficiency η_0 can be expressed as

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

where α_s is the supply leakage efficiency, defined as the fraction of air moved by the air handler that enters the building

α_r is the return leakage efficiency, defined as the fraction of air moved by the air handler that comes from the building

β_s is the supply conduction efficiency based on standard heat exchanger theory

β_r is the return conduction efficiency based on standard heat exchanger theory

ΔT_r is the temperature difference between the house and the air around the return duct

ΔT_s is the temperature difference between the house and the air around the supply duct

ΔT_e is the temperature change across the conditioning equipment

For a detailed derivation of this equation, see Palmiter and Francisco (1997). This equation has the features 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 the house temperature and those in the zones where the supply and return ducts are located. Eq. (1) is identical to that found in Standard 152P for delivery effectiveness, which has the same definition as delivery efficiency.

There are several important implications of Eq. (1). One is that, since the first term is independent of temperature, the delivery efficiency can be no better than the product of the supply-side leakage and conduction efficiencies. Another is that if the return-side ambient temperature is the same as the house temperature then the return duct has no impact on the delivery efficiency. Further, as the temperature change across the equipment decreases the delivery efficiency also decreases. This raises concern about heat pumps and air conditioners, which tend to have much smaller temperature changes than do other types of equipment such as furnaces. Eq. (1) also suggests that, if all else is held constant, a decrease in equipment capacity results in a reduction of the delivery efficiency. The situation is less clear for air handler flow rate because both the temperature rise across the equipment and the conduction efficiency depend on the flow rate. If there are no conduction losses, an increase in air handler flow rate will result in a reduction of delivery efficiency. Note that this does not address any impact on the efficiency of the equipment, such as a heat pump, due to a change in the flow rate over the coils.

Distribution Efficiency

While the delivery efficiency is an important measure of efficiency 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 via such mechanisms as 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. The change in losses through the ducts due to the change in buffer space temperature is not considered to be regain, but rather is accounted for by using the warmer (or colder) temperature in the temperature-dependent terms of the delivery efficiency.

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 directly), 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 an offset to the efficiency instead of as a multiplier. The offset, η_{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 (1991a, 1991b, 1992) and incorporated by ASHRAE (1993). In the case of return-dominated leakage ($\alpha_s > \alpha_r$), the offset causes the distribution efficiency to increase relative to ignoring the infiltration interaction. 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 (for example, in the heating case, the house gets colder the longer the equipment runs).

The mathematical form of the interaction of unbalanced duct leakage with natural infiltration depends on whether the unbalanced leakage is less than or greater than twice the natural infiltration rate. Note that only infiltration through the building envelope should be considered for this calculation; the impact of infiltration through holes in the ducts is already accounted for in the delivery efficiency. In the homes tested in this study, all of the homes fell into the small unbalanced leakage category both before and after retrofit. Therefore, only the small unbalanced leakage case is presented here; for a discussion of the large unbalanced leakage case see Palmiter and Francisco (1997).

Let ΔT be the temperature difference between the house and outdoors and η_1 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). Then, for the small unbalanced leakage case

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

and

$$\eta_1 = \alpha_s\beta_s - \alpha_s\beta_s(1-\alpha_r\beta_r)\frac{\Delta T_r}{\Delta T_e} - \alpha_s(1-\beta_s)\frac{\Delta T_s}{\Delta T_e} - \frac{1}{2}(\alpha_r - \alpha_s)\frac{\Delta T}{\Delta T_e} \tag{3}$$

Regain. The amount of duct losses recovered to the conditioned space through regain depends greatly on the physical characteristics 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

$$f = \frac{(UA)_h}{(UA)_h + (UA)_{out}} \tag{4}$$

where $(UA)_h$ is the conductance from the buffer space to the house (or other conditioned space)

$(UA)_{out}$ is the conductance from the buffer space to outside the house, including to the ground, ambient, and via infiltration through the buffer space.

The regain factor is represented in the model as a multiplier to the fraction of energy lost by the ducts to unconditioned spaces. Note that efficiency losses due to return-side leakage are not energy losses to the buffer space. Since supply and return ducts can be located in different zones it is frequently necessary to use separate supply and return regain factors. As described in Davis et al. (1998), the distribution efficiency with separate supply and return regain factors can be expressed as

$$\eta = \eta_0 + f_s\left(1 - \eta_0 + \left(\frac{f_r}{f_s} - 1 - \beta_r\left(\frac{f_r}{f_s} - \alpha_r\right)\right)\frac{\Delta T_r}{\Delta T_e}\right) - \eta_{in} \tag{5}$$

Field Measurements

Overview

The eight homes in the study were not chosen at random. Because the testing was to investigate the potential for savings due to aggressive air sealing retrofits, homes were selected to have large duct leakage to outside. In addition, homes with basements and homes that were too large to make data collection practical were excluded from the sample. All of these homes had gas furnaces, none of which were sealed combustion furnaces. During testing, the thermostat used to control the furnace was damaged and the results from the houses designated Sites 2 and 3 are questionable. These homes have been excluded from further discussion in this paper. Table 1 provides some of the pertinent physical characteristics of the remaining six homes and their duct systems. Only supply duct information is given since supply losses have a much greater impact on the efficiency than do similar return losses.

Table 1. Test home characteristics

	House			Supply Ducts		
Site	**Floor area (ft^2)**	**Volume (ft^3)**	**Stories**	**Surface area (ft^2)**	**% in unconditioned spaces**	**No. of open registers**
1	2202	20876	2	692	68	16
4	1334	10645	1	174	100	5
5	1345	10750	1	355	100	9
6	1744	13650	1	429	100	8
7	1840	14677	2	402	82	13
8	1390	10894	1	390	100	10
Avg.	1642	13582		407	92	10

Coheat methodology

The short-term coheat test used for this study involved alternately heating the home by the furnace and by electric resistance space heaters in shifts lasting about 2½ hours. Temperature measurements are taken in each heating zone (usually defined as any room with a heating register), in each buffer space in which ducts are located, outside, in the supply and return plenums, in the return register, and in as many supply registers as is possible with the remaining channels on the dataloggers. Amperage is measured for the air handler fan and gas valve to indicate when each of these is on and off. True power meters are placed on the mains to record electric consumption. The gas meter was clocked to determine the rate of gas consumption.

Average temperatures in each heating zone are recorded during periods of furnace operation. To minimize bias due to the warming of the ducts, the average control temperatures are reset when the furnace shuts off for the first time after a minimum of 1.5 hours of heating by the furnace has passed. The furnace continues to heat the house for at least one more hour (such that the time between the average reset and the end of the furnace period contains an integral number of furnace cycles), and average heating zone temperatures are recorded during this time.

The electric resistance heaters (called coheaters), which are distributed throughout the house to approximate the amount of heat input to each zone, are then operated such that the temperature in each zone is maintained at the recorded average from the furnace period. Similar to the furnace mode, only the second half of the coheat period are used for comparison to the furnace period so that the heat recovered by the cooling of the ducts does not bias the results. The ratio of the electric consumption of the coheaters to the heat supplied by the furnace is then a measure of the distribution efficiency.

This project was the first in which this technique was applied to gas furnaces. All previous coheat studies were confined to electric furnaces (or heat pumps operated in resistance-only mode). This made the comparison of energy consumption by the furnace and the coheaters simple since electric resistance operates at 100% efficiency. However, this is not the case with gas furnaces, where the combustion efficiency varies from house to house and the energy content of the gas is not measurable on-site. To determine the heat supplied by the furnace, the furnace combustion efficiency was measured and combined with the flow rate from the gas meter reading and an estimate of the heating content of the gas (provided by the gas utility).

At the end of each coheat test a steady-state test is run. In this test the thermostat is turned up so that the furnace will run constantly for an extended period of time. Temperature data are still recorded during this test. In homes where enough supply registers were instrumented, combining supply register temperatures from this test with measured register flow rates can provide an estimate of the steady-state delivery efficiency.

Other Measurements

In addition to the coheat tests, other measurements were taken at each of the test homes to assist in the analysis of the data and to allow for direct application and comparison of the duct efficiency model. The measurements used for modeling include envelope leakage using a blower door in depressurization mode with the registers sealed, supply and return duct leakage using a Duct Blaster™ (a duct pressurization device), flow hood and static pressure measurements at each register with the air handler operating, and static pressure measurements in the supply and return plenums with the air handler operating. Duct leakage tests were performed to get both total duct leakage and leakage to outdoors.

Results

Measured Results from Additional Diagnostic Tests for Application of the Duct Model

The first two columns of Table 2 show results from blower door envelope leakage tests with registers sealed, including cfm 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. The results from these tests were used in the portion of an infiltration model developed at Lawrence Berkeley Laboratory (Sherman and Grimsrud 1980) that is based on stack effect only to estimate natural infiltration rates. Wind effects in the residential areas in which these homes were sited are not likely to be very important.

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 2.

Table 2. House and Duct Leakage at 50 Pa

	House leakage		Total supply duct, cfm		Supply duct to outside, cfm		Return duct to outside, cfm	
Site	**cfm**	**ACH**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
1	3495	10.0	465	305	377	220	243	120
4	3996	22.5	478	265	411	179	689	78
5	2385	13.3	482	222	322	89	280	63
6	2514	11.1	613	120	580	95	97	42
7	2307	9.4	398	44	355	27	529	327
8	2833	15.6	438	210	394	149	450	81
Avg.	2922	13.7	479	194	406	126	381	118

The duct leakage under operating conditions depends on the static pressures that exist in the ducts at the leakage locations. Static pressure measurements were made with a pitot tube pointed upstream at each register and in the plenums, and engineering judgment was used to estimate an "average" static pressure experienced by the leaks. Table 3 shows these average system static pressures and the resulting leakages. Table 4 shows the sum of the flows through the registers and the air handler flow calculated as the register flow plus total supply duct leakage at operating conditions.

Table 5 shows the temperature differences that are required for the model: ΔT_s, ΔT_r, ΔT, and 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 differences from each space are weighted by duct surface area to obtain an overall temperature difference.

Table 3. Distribution System Pressures and Duct Leakage at Operating Conditions

	System Static Pressure (Pa)				Duct Leakage (cfm)					
	Supply		Return		Supply Total		Supply to Out		Return to Out	
Site	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	10.6	13.5	10.6	13.5	195	134	157	86	87	52
4	7.8	8.4	10.6	11.7	174	96	152	69	358	22
5	11.7	13.1	20.6	20.6	175	99	127	35	170	38
6	13.7	15.0	12.0	13.0	293	57	285	45	42	20
7	18.6	17.6	15.0	15.0	231	20	206	19	278	164
8	11.2	20.3	7.0	29.0	168	117	168	86	156	58
Avg.	12.3	14.6	12.6	17.1	206	87	182	57	182	59

Table 4. Register and Air Handler Flows

	Register Flows (cfm)		Air Handler Flows (cfm)	
Site	Pre	Post	Pre	Post
1	830	891	1025	1025
4	521	599	695	695
5	542	605	717	704
6	727	963	1020	1020
7	951	1080	1182	1100
8	632	683	800	800
Avg.	700	804	906	891

Table 5. Pertinent Temperature Differences

	Pre-Retrofit (F)				Post-Retrofit (F)			
Site	ΔT_s	ΔT_r	ΔT	ΔT_e	ΔT_s	ΔT_r	ΔT	ΔT_e
1	8.6	10.4	34.4	49.9	13.2	11.3	30.1	49.4
4	14.0	15.8	25.1	68.4	18.9	18.9	30.2	69.2
5	21.8	21.8	41.4	50.6	23.2	23.2	42.8	51.6
6	11.2	26.0	25.7	51.3	25.3	30.5	25.3	51.2
7	13.9	9.1	31.1	74.6	12.9	10.1	28.1	79.3
8	23.3	26.3	32.1	66.0	22.4	22.3	28.2	65.5
Avg.	15.5	18.2	31.6	60.1	19.3	19.4	30.8	61.1

Efficiency Results

Table 6 shows the pre- and post-retrofit leakage efficiencies α_s and α_r and conduction efficiencies β_s and β_r, as well as the modeled delivery efficiency η_0 during cycling. The leakage to outside under operating conditions from Table 4 and the air handler flow from Table 5 were used to calculate α_s and α_r. Since β_s and β_r 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.

Table 7 shows the supply and return regain factors f_s and f_r and the infiltration interaction term η_{in}, which are required to model the distribution efficiencies at each site. The regain factors were estimated based on visual inspection of the zones in which the ducts are located. In those cases where there are multiple zones for the supply and/or return ducts, the regain factors from each space were weighted by duct surface area to obtain an overall regain factor. Ducts in exterior walls were assigned a regain factor of 0.5. An infiltration rate of 4.6 ACH was assumed for the buffer spaces, which is based on the median of crawl space flows for seven homes in the Pacific Northwest (Palmiter & Francisco 1996; Francisco & Palmiter 1996). Negative infiltration interaction terms indicate return-dominated leakage, and increase the efficiency relative to ignoring the terms.

Table 8 provides a summary of the measured and modeled distribution efficiency results. The first two columns show the measured and modeled pre-retrofit duct distribution efficiency results, with the difference between measured and modeled results shown in the third column. The post-retrofit results are shown in the fourth, fifth, and sixth columns. These results are shown graphically in Fig. 1.

Table 6. Leakage and Conduction Efficiencies and Modeled Delivery Efficiency During Cycling

	Pre-Retrofit					**Post-Retrofit**				
Site	α_s	β_s	α_r	β_r	η_0 (%)	α_s	β_s	α_r	β_r	η_0 (%)
1	0.847	0.849	0.915	0.977	65.4	0.916	0.893	0.949	0.978	76.4
4	0.782	0.891	0.485	0.826	60.4	0.901	0.961	0.968	0.868	82.4
5	0.823	0.918	0.763	0.974	65.1	0.950	0.923	0.946	0.974	82.8
6	0.721	0.893	0.959	0.941	60.0	0.956	0.905	0.980	0.941	81.2
7	0.826	0.829	0.765	0.969	60.8	0.983	0.969	0.851	0.962	90.7
8	0.790	0.874	0.805	0.911	60.0	0.893	0.880	0.927	0.912	72.3
Avg.	0.798	0.876	0.782	0.933	62.0	0.933	0.901	0.937	0.928	81.0

Table 7. Regain Factors and Infiltration Interaction Terms

	Pre-Retrofit			**Post-Retrofit**		
Site	f_s	f_r	η_{in}	f_s	f_r	η_{in}
1	0.093	0.036	0.0235	0.093	0.036	0.0101
4	0.173	0.173	-0.0545	0.173	0.173	0.0146
5	0.043	0.043	-0.0245	0.043	0.043	-0.0017
6	0.055	0.035	0.0597	0.055	0.035	0.0059
7	0.067	0.038	-0.0127	0.067	0.038	-0.0234
8	0.032	0.067	0.0036	0.032	0.067	0.0073
Avg.	0.077	0.065	-0.0008	0.077	0.065	0.0021

Keep in mind that these distribution efficiency results need to be multiplied by the combustion efficiency (which was between 76% and 78% for all houses except at Site 5, where it was 70%) to get an overall system efficiency including the furnace.

In many cases, such as utility retrofit programs, it is the energy savings which is the most important result. Therefore, the ability of the model to predict the savings due to changes to the duct system also needs to be investigated. The savings, defined as the reduction in furnace output required to meet the house load, is calculated as

$$\left(1-\frac{\textit{pre retrofit distribution efficiency}}{\textit{post retrofit distribution efficiency}}\right)\times 100 \qquad (6)$$

The seventh and eighth columns of Table 8 show the estimated savings due to the retrofit based on measured and modeled distribution efficiencies, respectively, and the final column shows the difference between measured and modeled savings estimates. Figure 2 compares the savings estimates graphically.

Table 8. Modeled and Measured Distribution Efficiency Results

	Pre-Retrofit η (%)			Post-Retrofit η (%)			Savings (%)		
Site	**Model**	**Meas.**	**Diff.**	**Model**	**Meas.**	**Diff.**	**Model**	**Meas.**	**Diff.**
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
Avg.	64.5	64.7	-0.2	81.9	77.4	4.5	20.9	16.1	4.8

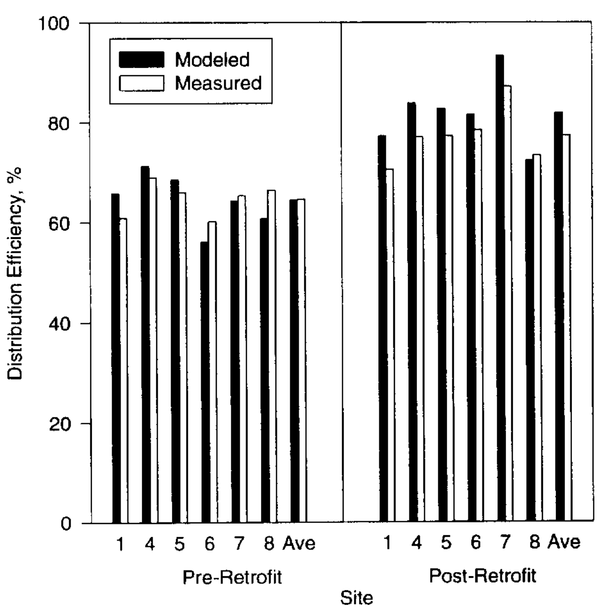

Fig. 1. Comparison of modeled and measured distribution efficiency estimates.

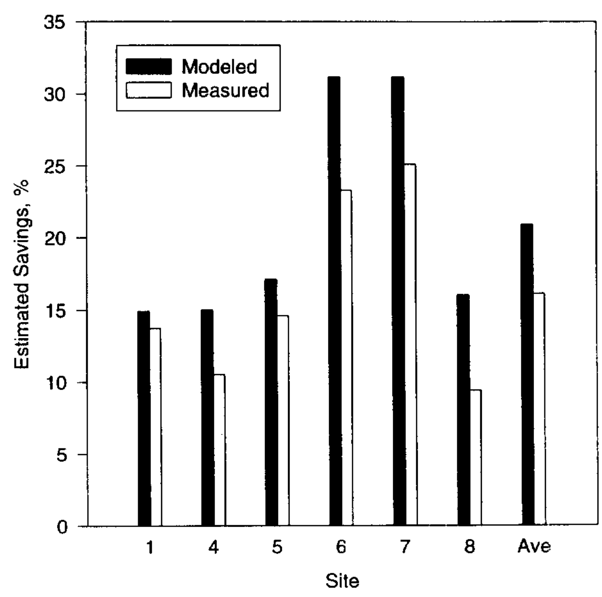

Fig. 2. Comparison of modeled and measured predictions of savings.

Table 8 shows that all of the pre-retrofit comparisons of measured to modeled 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. Considering which parameters are most difficult to measure, the most likely sources of discrepancy are: 1) inaccurate air handler flow estimates; 2) inaccurate regain factor estimates; 3) inaccurately estimated average static pressure at the leaks in the ducts, resulting in an inaccurate prediction of the duct leakage at operating conditions; and 4) the fact that cycling losses are not incorporated in the model.

One might expect that the comparison of modeled to measured results would improve after the retrofits were performed because the air leakage fraction, which can be very difficult to determine accurately, is largely eliminated. However, errors in several large factors may tend to cancel each other out in the pre-retrofit case but not in the post-retrofit case. For example, overestimates of leakage counteract overestimates of regain. In the post-retrofit modeling, the combination of an overestimated regain factor and neglecting cycling losses would tend to systematically overestimate the distribution efficiency, without the leakage helping to cancel out some of these errors.

When estimating the savings due to the retrofits, the model averages 4.8 percentage points higher than measured data. The average predicted savings from the model is 20.9% compared to 16.1% based on the measured efficiency results, with the model predicting higher savings in every house. The model well identifying houses at which savings are the largest (Sites 6 and 7).

In three of the houses discussed in this paper, a sufficient number of supply register temperature measurements were taken to 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 9 shows these comparisons along with the difference between the modeled and measured values.

This table shows that, with the exception of Site 4 post-retrofit, the steady-state modeled results are within three percentage points of the measured values. It is unknown why there is such a large disagreement for the post-retrofit case at Site 4. The results also show that there is only a small difference between the modeled cycling and steady-state delivery efficiencies (see Table 6 for the cycling delivery efficiencies), with the largest being 2.4 percentage points. Because the leakage and conduction efficiencies are assumed to be constant, the difference between cycling and steady-state results is due solely to temperature changes.

Table 9. Modeled vs. measured delivery efficiency under steady-state conditions

	Pre-Retrofit Delivery Efficiency η_0 (%)			Post-Retrofit Delivery Efficiency η_0 (%)		
Site	**Modeled**	**Measured**	**Difference**	**Modeled**	**Measured**	**Difference**
4	58.0	56.6	1.4	81.8	70.6	11.2
5	64.0	65.4	-1.4	81.0	78.3	2.7
8	58.3	61.2	-2.9	70.8	67.9	2.9
Avg.	60.1	61.1	-1.0	77.9	72.3	5.6

Summary

A simple model for predicting steady-state distribution efficiency was applied to six gas-heated homes in the Puget Sound region and compared to pre- and post-retrofit measured efficiency results obtained using the short-term coheat method. The model accounts for the complex interaction between

supply and return duct systems, between conduction and leakage losses, and between unbalanced duct leakage and natural infiltration. Regain factors account for duct losses that are recovered via conduction to the conditioned space as useful heat. All of the inputs to the model were either measured or estimated based on visual inspection; no default values were used.

The comparisons of modeled and measured data are encouraging, especially considering many of the uncertainties inherent in some of the model inputs, such as flow through the air handler and regain. This suggests that with sufficient measurements (and appropriate estimates regarding items like regain) the distribution efficiency can be predicted by the model to within a few percentage points of actual values.

The modeled distribution efficiency results were within seven percentage points of the measured values in all cases, and on average were lower by 0.2 percentage point pre-retrofit and higher by 4.5 percentage points post-retrofit. It is expected that the modeled values will be higher than measured results because the model does not account for cycling losses.

The model is also higher by an average of 4.8 percentage points compared to measured data when predicting savings due to the retrofits. Since the savings is of perhaps more interest than the actual efficiencies to utilities that are running retrofit programs, this is an encouraging and important result. In addition to predicting a comparable average savings to that based on measured data, the model successfully distinguishes between groups of houses with the largest savings and groups that show more modest savings.

Caution must be taken when interpreting the results because of the small sample size and because the homes were selected to have a large amount of supply-side duct leakage to outdoors relative to the air handler flow rate. As such, they should not be considered to be either a random or representative sample of the overall housing stock.. It is important that the model be applied to a much larger sample of homes with different characteristics to verify that it will provide acceptable results in general.

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