Are Your Ducts All in a Row?
Duct Efficiency Testing and Analysis for 150 New Homes in Northern California

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ABSTRACT

An impact evaluation was recently completed for PG&E's residential new construction program. Key measures in this program included high efficiency central air conditioners and enhanced duct installations. To evaluate this program, over 300 comprehensive building surveys were conducted, and a calibrated engineering analysis was developed to compare as-built homes with reference case homes.

To evaluate the duct component of the program, "duct blaster" tests were conducted on a subset of 158 homes to establish duct system performance with respect to leakage. Information about the duct system for each home (including physical dimensions, location, insulation levels, and leakage) was then run through a distribution system efficiency model. The model, developed by LBNL, is based on the draft ASHRAE 152P Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems 1997. The distribution system efficiency estimates were combined with Micropas simulation results and engineering estimates of energy consumption for non-HVAC end uses to provide "whole building" usage estimates. Participant and nonparticipant energy usage could then be calibrated to customer bills and compared to establish program savings.

This paper focuses on the duct system analysis portion of the evaluation project. The duct testing and analysis are described. Duct leakage test results are then presented along with a comparison of test results for program participants and a matched group of nonparticipants. Finally, calculated distribution system efficiencies are compared against default HVAC Duct Efficiency Factors that are assumed for California Title 24 compliance modeling.

This project provides a relatively large-scale look at duct system efficiency in new homes. In addition, the modeling approach provides a method for integrating duct test data into a Micropas simulation analysis.

Introduction

Forced air distribution systems can have a significant impact on the energy consumed in residences. A number of utility programs exist to improve duct efficiencies through duct testing, repair, and contractor training. The primary goal of these programs is to make tight duct construction commonplace through educating contractors about typical problems such as inadequate joint sealing, improper use of adhesive connections, and a lack of sealing at the blower housing.

Duct sealing and insulation programs have had variable impacts on air distribution system efficiencies. Air distribution system leakage reduction from duct testing and repair ranges from 22% improvement (Karins et al, 1997) to 70% improvement (Palmiter and Olsen, 1994) with values typically around 60% (Bissei and Davis 1995; Cummings et al 1990, Downey 1994; Jump and Modera 1994; Proctor 1991; Strunk, 1996.)

Since duct losses can account for 30-40% of residential HVAC energy consumption (Cummings & Tooley 1989; Lambert & Robison 1989; Davis 1991; Modera et al 1992; Palmiter & Francisco 1994; Stunk et al 1996; Walker et al 1996), PG&E has encouraged the installation of efficient duct systems by including a duct component in their residential new construction program (the Comfort Homes program). The program also provided incentives for the installation of high efficiency central air conditioners, gas cooking, and gas clothes dryer stubs.

For the impact evaluation of PG&E's residential new construction program, savings estimates were required for the key program measures. The approach used for this evaluation was a structured billing analysis referred to as an SAE (statistically adjusted engineering method). In this method, engineering estimates of energy use are calibrated to customer bills using a cross-sectional time series regression analysis. Estimates of savings for each key program measure are developed by comparing calibrated engineering results for participants against results for nonparticipants. On-site surveys on over 300 homes, were conducted to support the analysis. Duct tests were conducted on a subset of 158 sites to provide additional data on the efficiency of the air distribution systems.

Because enhanced duct installation was a key program measure, a cost-effective method was required to identify differences in duct efficiencies between participants and nonparticipants. The approach chosen for the evaluation was the use of duct blaster testing to determine duct leakage, and the translation of duct leakage measurements into distribution system efficiency estimates using algorithms based on the draft ASHRAE 152P Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems.

The primary purpose of this paper is to report results of the duct testing and analysis portions of this relatively large-scale impact evaluation.

Background

A number of methods exist for testing air distribution system efficiencies. There are at least three quantitative tests appropriate for large-scale projects (Proctor et al 1993): blower door subtraction, blower door and flow hood combination, and duct blaster. In the blower door subtraction method, the house is first pressurized to 50 Pa with a blower door to obtain the total leakage of the home. Next, a second blower door flow reading at 50 Pa is taken with the duct registers and return grill sealed. The difference between the two flow readings is a measure of the leakage through the duct system. With the blower door and flow hood combination method, the registers are sealed and a flow hood is attached to the return grill. The house is pressurized to 50 Pa with a blower door and the flow through the hood is used to approximate the duct leakage. With the duct blaster method, the registers are sealed, a variable speed fan is attached to the supply fan compartment or the return grill, and the air distribution system is pressurized to 25 Pa. The air flow into the ductwork is a measure of the leakage.

For this study, the duct blaster method was chosen for its simplicity and relative ease of use. No attempt was made to compare the merits of the various duct leakage tests. This issue is addressed in detail in the existing literature (i.e., Proctor et al 1993). The duct blaster test was chosen because the equipment is relatively compact, making for easy transportation, and because duct blaster tests do not require multiple equipment configurations like the blower door subtraction method and the blower door flow hood combination test. This simplicity keeps the test time short, and less obtrusive to the surveyed homeowner, a plus for large studies.

Equipment

The equipment used for this study is the Minneapolis Duct Blaster Systems' Series B unit with DG-3 digital gauges. A manual controller on the duct blaster is used to adjust the fan speed to obtain the reference pressure. The gauge samples the fan speed and duct pressure to calculate a volume air flow into the duct system, based on manufacturer calibration. The digital gauges have rated accuracy of ±1%, and were chosen to reduce the possibility of reading error compared with analog gauges.

The duct blaster consists of the following major components: a fan, a digital pressure measurement gauge, a fan speed controller and a flexible extension duct. The duct blaster system chosen for the study is manufactured by the Energy Conservatory in Minneapolis, and meets the flow calibration specifications of the standards. It is capable of moving up to 1,350 CFM against 50 Pa of back pressure and has a flow accuracy of +/-3%.

Duct Blaster Technique

The duct blaster method used in this study involves pressurizing the full air distribution system to a reference pressure and measuring the air flow needed to maintain that pressure. This air flow is the total leakage from the system, and is representative of the operating leakage when the reference pressure is similar to the average operating pressure.

Duct leakage is measured by first connecting the duct blaster system to the ducts at either a central return grill or at the air handler access door. After sealing off all the supply and return registers, and combustion or ventilation air inlets, the duct blaster is used to pressurize the entire duct system to a standard testing pressure. The duct pressure at which the test is conducted is representative of the average actual duct operating pressure and is typically predetermined by the program test protocol (e.g., 25 Pa or 50 Pa). In this case, a reference pressure of 25 Pa was chosen. The air flow needed to maintain the reference pressure is generated by a calibrated variable-speed fan. The pressure across the fan required to maintain the reference pressure in the duct system is measured, and converted to air flow in cfm based on calibration tests performed by the manufacturer of the duct blaster equipment. The air flow is the total duct leakage at the reference pressure.

Duct Leakage Disaggregation

The total duct leakage value obtained from the duct blaster test consists of leakage to outside plus leakage to inside. Since air lost to the interior helps condition the space, it does not affect the energy consumption of the HVAC system. For this reason, it is necessary to separate out the losses to the unconditioned spaces and outside from the losses to the conditioned spaces. This disaggregation, along with the calculation of the overall thermal performance of the distribution system, is accomplished with a spreadsheet application from Lawrence Berkeley National Laboratory (LBNL) based on calculation algorithms from ASHRAE Standard 152P.

Duct leakage to the outside was calculated using measured total leakage data and assumed disaggregation fractions. Based on the homes in the study, is was assumed that 75% of the air loss was from the supply ducts and 25% of the air loss was attributable to the return ducts. In addition, 15% of the total duct leakage was assumed to be conditioned spaces, and did not contribute to losses.

Duct Efficiency

In order to combine duct test results with Micropas simulation results, distribution system efficiency estimates were required for the project. From the disaggregated duct leakage values, it was possible to utilize some of the algorithms developed for Standard 152P to estimate the efficiency of the air distribution system. The model was developed to better determine actual duct efficiencies utilizing site-specific data.

In addition to the duct leakage values, the procedure requires information about the supply and the return duct location, the size of the home, the ambient conditions, duct surface area, duct insulation level, heating and cooling system capacities and fan flow. Table 1 summarizes the input parameters required for the model and the source of these inputs. Some data were collected during the on-site surveys while others were calculated based on surveyed data or assumed from standard practice and ASHRAE protocols. In addition, standard CEC climate data were utilized for weather-related inputs. The following table lists each input and its source.

Table 1. Duct Efficiency Model Input Parameters

Parameter	Surveyed	Calculated or Lookup[1]	Assumed
Conditioned Floor Area, and House Volume	✓		
Supply & Return Duct Surface Areas		✓	
Fraction of Ducts in Conditioned Space			✓
Supply & Return Duct R-values	✓		
Thermostat Setpoint, Heating & Cooling	✓		
Heating & Cooling Design Temperatures		✓	
Design Wetbulb Temperature		✓	
Indoor Wetbulb Temperature		✓	
Attic Solar Gain Reduction [y/n]	✓		
Equipment Heating & Cooling Capacity	✓		
Heating & Cooling Fan Flow		✓	
Heating & Cooling Supply & Return Duct Leakages	✓		
Duct Thermal Mass Correction	✓		
Equipment Efficiency Correction	✓		
Is The Attic Vented?	✓		
Is There A Thermostatic Expansion Valve?		✓	
Is Heating System A Heat Pump?	✓		

[1]Calculated values are based on survey data or lookup part numbers in manufacturer's literature.

Parameters that were not directly recorded during the on-site surveys but were calculated as part of the analysis were the duct surface area and fan flow. Equations 1 and 2 show how these parameters are calculated using the Standard 152P-based model. The results provide seasonal thermal distribution system efficiencies for both heating and cooling systems that are used later in computing energy consumption.

$$Cooling\ Capacity \times 340\ cfm/ton = Supply\ Fan\ Flow \qquad \text{Eqn. 1}$$

$$Supply\ Duct\ Surface\ Area = 0.27 \times Floor\ Area \qquad \text{Eqn. 2a}$$

$$Return\ Duct\ Surface\ Area = K_r \times Floor\ Area \qquad \text{Eqn. 2b}$$

where $K_r = 0.05$ if there is one return register and 0.10 if there are two

The overall design and seasonal heating and cooling thermal distribution system efficiency calculations are not complicated, but involve a rather large number of steps, therefore, the reader is referred to the source (ASHRAE Standard 152P) for details.

Energy Consumption Calculation

Once the air distribution system delivery efficiencies were known and the loads calculated with Micropas, it was easy to develop estimates for the HVAC energy consumption. Using the system efficiencies obtained in the on-site surveys, energy usage for cooling and heating was calculated as follows:

$$Energy = \frac{load}{systeff \times ducteff} \times conv \qquad \text{Eqn. 3}$$

where:

load = Micropas load estimate in kBtus for cooling or heating

systeff = system efficiency for cooling (SEER) or heating (AFUE)

ducteff = duct efficiency (fraction between 0.0 and 1.0)

conv = conversion factor to translate from kBtu to kWh or therms

Energy Savings Calculations

For the evaluation, estimates of energy savings above the Title 24 reference were determined by subtracting "as-built" energy usage from reference energy usage. Using Equation 3 above, as-built energy usage reflects the as-built loads from Micropas, the actual system efficiencies (SEER and AFUE), and the calculated duct efficiencies. Reference energy use reflects the Micropas reference loads, standard system efficiencies (10 SEER and 0.78 AFUE), and reference duct efficiencies (based on the nonparticipant average for cooling and heating).

Results

Ultimately, the goal of this study was to produce energy savings estimates for the various measures rebated under the Comfort Home Program. Along the way toward this goal, a number of interesting results relating to duct leakage testing were found.

As shown in Figure 1, the range of duct leakage is roughly the same for both program participants and nonparticipants. Data for this chart were sorted into lists of increasing duct leakage. Through sorting equal numbers of participant and nonparticipant observations in this way, it is possible to see trends in data where the ranges overlap. So while the ranges of duct leakage are the same for program participants and nonparticipants, the figure shows that the average duct leakage is significantly lower for participants. The most likely explanation for this behavior is that most nonparticipant contractors built more leaky duct systems, but a few did a good job even without incentives, and while most participant contractors built better-sealed duct systems, a few built leaky ones. It is also possible that the leakage in some duct systems may have increased over time.

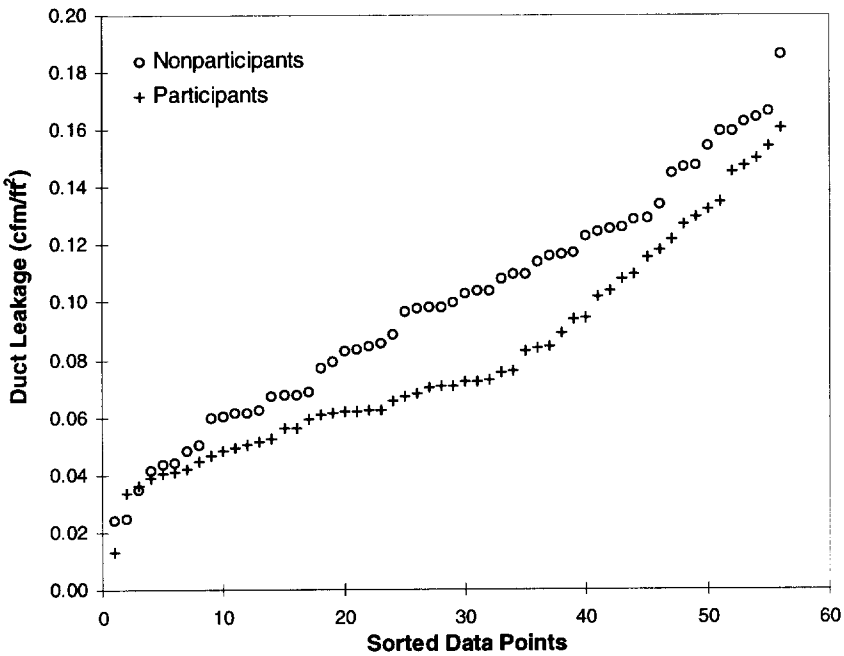

Figure 1. Measured Duct Leakage Normalized to Home Floor Area

The calculated heating and cooling seasonal duct efficiencies are presented Figure 2 and Figure 3. The results clearly show that the CEC default duct efficiency assumptions for 1-story homes are at the very highest end of measured results, while the CEC defaults for 2-story homes are so high that they are represented by only two homes. These findings support the decision to adjust the reference duct efficiency to match the average measured nonparticipant efficiency.

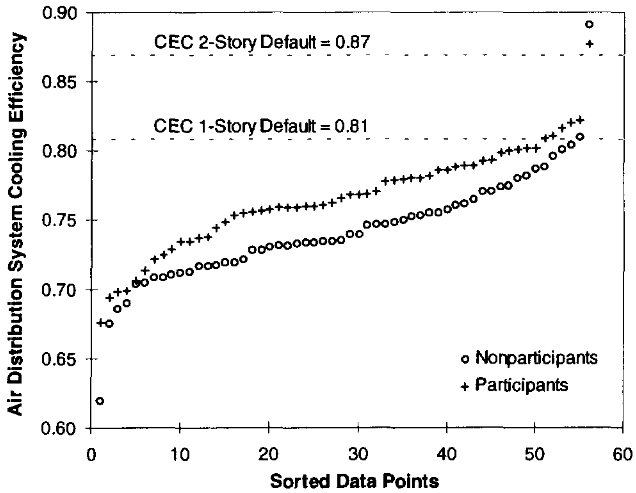

Figure 2. Measured Air Distribution System Cooling Efficiency

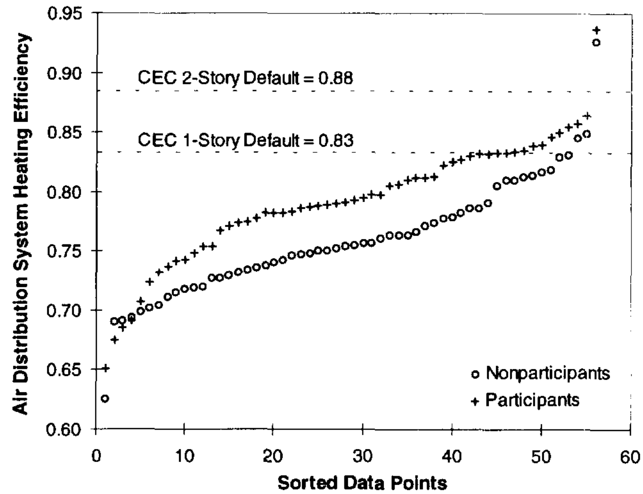

Figure 3. Measured Air Distribution System Heating Efficiency

It appears that the default duct efficiencies applied to external load calculations in Micropas (and also published in the CEC compliance manual) tend to overstate actual duct efficiencies. The effect of this overstatement may be that both participant and nonparticipant "as-built" duct systems show lower efficiencies than the default Micropas efficiencies. This effect could lower gross program savings relative to an artificially efficient reference case (although net impacts that rely on differences between participants and nonparticipants are unaffected). To avoid this problem, the reference duct efficiencies were adjusted to reflect more realistic values using the average nonparticipant duct efficiencies for heating and cooling.

Duct Efficiency Parameters

Average duct leakage and duct efficiency estimates for all study homes are presented in Table 2. As the table indicates, the participants performed better than the nonparticipants both in terms of duct leakage (lower) and duct efficiency (higher). Duct efficiency differences between participants and nonparticipants were statistically significant at the 99% confidence level. As expected, the average duct efficiencies were lower than the efficiencies used in the compliance model.

Table 2. Duct Efficiency Parameters

	Participants	Nonparticipants	Average	Compliance Value
Duct leakage, cfm	144	187		
Duct leakage, cfm/sf	0.081	0.100		
Cooling efficiency	0.768	0.741	0.759	0.860
Heating efficiency	0.794	0.756	0.781	0.873

Conclusions

The duct blaster technique was effective for obtaining sufficiently accurate leakage data to satisfy the California utility program review standards. Beyond this, the duct blaster is easy to operate, and fairly transportable. The duct analysis model, which uses algorithms from ASHRAE Standard 152P, provides a useful method for calculating the seasonal and design heating and cooling air distribution efficiencies from survey data. The spreadsheet tool developed by Iain Walker of LBNL to implement the standard saves considerable time—especially when evaluating data from a large number of sites.

A comparison of participant and nonparticipant duct leakage estimates shows a reduction of 19% for the PG&E program participant homes (0.081 cfm/sf versus 0.100 cfm/sf). This reduction in duct leakage (and subsequent increase in distribution efficiency) was much lower than initially predicted. Indeed, the gross savings developed during the evaluation were only about half of the initial program estimates.

The lower savings estimates do not appear to be driven by nonperformance of participating homes. Rather, the nonparticipant homes appear to have increased in efficiency over homes built in past years. Nonparticipant leakage estimates of 187 cfm (see Table 2) are much lower than results reported in earlier studies which showed average duct leakage to exceed 250 cfm in some cases (Jump 1996, Modera 1993).

The improved distribution system performance in nonparticipant homes is probably the result of several factors. First, program spillover may be at work as several nonparticipant builders claimed their past association with the PG&E program contributed to their use of enhanced duct installation practices. Second, increased oversight by building inspectors may be contributing to improved construction practices. Finally, increased awareness of better duct installation practices has resulted from the work of organizations such as LBNL and the Florida Solar Energy Center.

Finally, the duct efficiency calculations from this study show that the CEC default assumptions for heating and cooling duct efficiencies may be significantly higher than the duct efficiencies in typical new homes.

Acknowledgments

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