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Measuring residential duct efficiency with the short-term coheat test methodology

Paul W. Francisco [a,*], Jeffrey Siegel [b], Larry Palmiter [c], Bob Davis [c]

[a] School of Architecture, Building Research Council, University of Illinois, 1 E. St. Mary's Rd., Champaign, IL 61820, USA
[b] Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 1 University Station C1752, Austin, TX 78712-1076, USA
[c] Ecotope Inc., 4056 9th Ave. NE, Seattle, WA 98105, USA

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Abstract

Assessing the thermal efficiency of a forced-air distribution system is difficult, in large part because of interactions between energy loss mechanisms and other building characteristics. This paper describes short-term coheating, a method of measuring the thermal efficiency of residential heating and cooling distribution systems in situ, and presents the results of a series of studies that utilized the short-term coheat methodology. Short-term coheat tests were conducted in 53 residential buildings including both site-built and manufactured housing. The magnitude of the distribution efficiency, defined as the ratio of the energy required to heat the building if there were no duct losses to the actual heating energy required, ranged from less than 50% for homes with disconnected ducts to more than 90% for well sealed and insulated systems. Duct retrofits were also performed at 20 of the test sites and, following the retrofits, on average, the homes required 16–17% less heating energy. These results show that residential distribution system losses can be responsible for substantial energy loss and that duct retrofits are a viable energy conservation strategy for homes with distribution systems located outside of the conditioned space.

Keywords: Heating system; Duct efficiency; Forced-air; Duct air leakage; Single-family homes; Manufactured homes; In-situ measurements

1. Introduction

Energy losses and gains through residential HVAC duct systems can have a profound influence on heating and cooling energy use. In heating mode, ducts located outside of the conditioned space, such as in attics and crawlspaces, can lose heating capacity by both conduction and air leakage. In cooling mode the ducts can lose cooling capacity by conduction and air leakage, and in addition, there can be more complex impacts on air conditioning because of possible increased latent loads on the coil due to return-side air leakage. Although there are recent attempts to promote the installation of residential HVAC ducts within the conditioned space, much of existing and new US housing stock still has fully or partially exterior ducts.

A series of studies in the late 1980s and early 1990s quantified energy losses due to ducts in unconditioned spaces. Robison and Lambert [1] estimated an average distribution efficiency loss of 12% in 20 Oregon homes. Parker [2] found that homes heated with electric furnaces used 21% more energy for heating than did homes heated with baseboards, when normalized by floor area. In this same study, Parker found that the homes with baseboards had 41% less infiltration, which also impacts energy use. Cummings et al. [3] found that 24 Florida homes had air-conditioning energy use reduced by 18% after duct repairs were made.

These studies initiated a serious research effort aimed at quantifying the effects of duct leakage on energy use and, more generally, the distribution efficiency of residential thermal distribution systems. Losses due to conduction across duct walls have been acknowledged for a long time. There has also been acknowledgment that leakage has the potential to be significant. In 1960, Carrier [4] stated that experience indicated that residential supply duct leakage averaged 10%, with installation practice the greatest variable. They reported measured supply-side leakages of 5–30%, and recommended a 10% value when estimating loads if all ducts are in unconditioned spaces.

The first mention of duct leakage in the ASHRAE Handbook was in the 1975 edition of the Equipment volume [5], which had

* Corresponding author.
E-mail address: pwf@uiuc.edu (P.W. Francisco).

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two paragraphs on the subject. These paragraphs refer to duct leakage as ''related to static pressure and joint type'', and states that ''if leakage is uncontrolled, energy will be wasted, and the system may fail to perform as specified''. However, it also simply recommends that ''transverse joints be sealed where static pressures are above (249 Pa) 1.0 in. water''. This characterization of duct leakage implies an assumption that the ducts are put together well, and that the leakage is at seams and joints. There is no concern expressed about ducts that have been poorly installed, with possible partial or complete disconnects or poorly cut attachment holes. There is also no concern expressed about leaks at pressures on the order of typical residential systems, which usually have much lower pressures, even at the plenums.

By 1989, ASHRAE had added a section in the Handbook of Fundamentals regarding duct leakage [6]. This expanded on the discussion in the Equipment volume, and described different duct ''leakage classes'', where the duct leakage class is the leakage in cubic feet per minute (cfm) per (9.3 m^2) 100 ft^2 of duct surface area at a pressure of (249 Pa) 1.0 in. water. Mention is made of standards from as far back as 1972 to test the leakage of ducts. Again, however, there is an implied assumption that the leakage is at seams and joints.

It was in the latter half of the 1980s that measurement of duct leakage became more commonplace in existing homes. Some of the earliest documentation of the leakiness of residential duct systems can be found in Modera [7], Diamond [8], and Robison and Lambert [1]. The results of these studies are summarized, in terms of effective leakage area (ELA) are summarized in Modera [9]. These measurements raised the awareness that ducts often leak more than would be assumed based on their ''leakage class'', due to poor installation, failed connections, and failure of common sealing methods.

Though the tests available at the time were relatively primitive, and did not determine duct leakage under normal operating conditions of the conditioning system, these studies prompted further investigation of losses due to duct systems and the potential savings from retrofits. They also resulted in mathematical models being developed to estimate the duct efficiency based on several inputs. The first published model for duct efficiency was developed by Palmiter and Francisco [10,11] and modified by Francisco and Palmiter [12]. A similar model is the basis for a new ASHRAE standard on estimating the efficiency of thermal distribution systems [13]. These models showed that it is not enough to simply look at the leakage or the conduction. The various components of duct losses interact in complex ways. Therefore, detailed field measurements were required, both to establish the losses and potential savings and to validate the model.

The thermal efficiency of duct systems is often characterized by two different values. The first, and most simple, is the ratio of the conditioning energy delivered to the building through the registers to the conditioning energy put into the ducts by the conditioning equipment. This was referred to as the heat delivery efficiency by Palmiter and Francisco [10,11] and as the delivery effectiveness by ASHRAE [14]. The second measure of duct efficiency is the distribution efficiency. This includes more than the conditioning energy delivered through registers. It also includes such factors as recapture of duct losses and the effect of unbalanced duct leakage on the infiltration rate of the home. It is defined as the ratio of the energy required to heat the building if there were no duct losses to the actual energy required. This measure of efficiency does not include the efficiency of the conditioning equipment itself, but it does include losses on both the supply (positive pressure) and the return (negative pressure) side of the system.

The delivery effectiveness, η_{de}, is defined as:

$$\eta_{de} = \frac{\sum_i Q_i \rho_i (h_i - h_{in})}{W_{cap}} \quad (1)$$

where i is an index that goes from 1 to the number of supply registers, Q_i the airflow rate through supply register i (m^3/h), ρ_i the density of air flowing through supply register i (kg/m^3), h_i the enthalpy of air flowing through supply register i (J/kg), h_{in} the enthalpy of the indoor air (J/kg), and W_{cap} is the measured capacity of the heating or cooling equipment (W). The power consumption that is required to meet heating and cooling loads in a building, W (W), is defined as:

$$W = \frac{W_{cap}}{\eta_{dis}\eta_{eq}} \quad (2)$$

where η_{dis} is the distribution efficiency and η_{eq} is the equipment efficiency (both dimensionless).

Of the two duct efficiency metrics, delivery effectiveness is the easier to measure. With suitably accurate airflow, temperature, and humidity measurements at each of the registers, combined with a good estimate of the capacity of the conditioning equipment, this value can be calculated. For furnaces, the capacity of the equipment can be determined by measuring the energy input at the service meter and multiplying the input by the equipment efficiency. For electric furnaces, the equipment efficiency is assumed to be 1.0, whereas for combustion furnaces such as those utilizing natural gas and propane the combustion efficiency must be measured. For systems with compressors, it is necessary to use a combination of system airflow and temperature change across the coil (and, in cooling mode, humidity before and after the coil). Distribution efficiency, however, is much more difficult to measure. This is because the additional factors included in this value are not directly measurable. However, it is this efficiency measure that most directly relates to the total energy use, and therefore cost, required to condition a building.

This paper provides a large dataset of distribution efficiency that benchmarks duct efficiency in homes in the Pacific Northwest, provides data for duct efficiency and energy use models, and explores the value of duct retrofits. We present a series of studies that measured the distribution efficiency using a technique called short-term coheating. The short-term coheat test protocol alternates heating the house with the conditioning equipment and with space heaters. The space heater energy consumption represents the required heating energy with no duct losses. Therefore, by monitoring the energy consumption for both methods of heating it is possible to determine the distribution efficiency of the duct system.