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The impacts of duct design on life cycle costs of central residential heating and air-conditioning systems

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ABSTRACT

Many central residential HVAC systems in the U.S. operate at high external static pressures due to a combination of system restrictions. Undersized and constricted ductwork are thought to be key culprits that lead to excess external static pressures in many systems, although the magnitude of energy impacts associated with restrictive ductwork and the costs or benefits associated with addressing the problem are not well known. Therefore, this work uses annual energy simulations of two typical new single-family homes in two separate climates in the United States (Austin, TX and Chicago, IL) to predict the impacts of various external static pressure ductwork designs from independent HVAC contractors (using both flexible and rigid sheet metal ductwork materials) on annual space conditioning energy use. Results from the simulations are combined with estimates of the initial installation costs of each duct design made by each contractor to evaluate the total life cycle costs or savings of using lower pressure duct designs in the two homes over a 15-year life cycle. Lower pressure ductwork systems generally yielded life cycle cost savings, particularly in homes with PSC blowers and particularly when making comparisons with constant ductwork materials (i.e., comparing flex only or rigid only).

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1. Introduction

Many central residential heating, ventilating, and air-conditioning (HVAC) systems in the U.S. have substantially higher external static pressures than specified by most standardized test procedures [1] due to a combination of common system restrictions, including high pressure drop filters, cooling coils, heating elements, ductwork, and fittings [2–8]. Among these restrictions, undersized and constricted ductwork is thought to be a key culprit that leads to excess external static pressures, particularly for compressible flexible ductwork materials [9]. Excess static pressures can have negative energy impacts depending on the type of blower motor used in the air handling unit (AHU) and the level of excess static pressure [10,11]. Increasing diameters in duct designs and specifying low-resistance duct materials can reduce system pressures [12] but may also increase the surface area for heat transfer to occur across ductwork installed in unconditioned spaces [13]. Consequently, the combined impacts of duct design details and external static pressures on energy consumption are complex, as the relationships between pressure, fan efficiency, fan power draw, airflow rates, and heating and cooling capacities are not straightforward and depend on the type of blower motor used in the AHU. Additionally, there is a lack of information on the overall life cycle cost implications of lower static pressure duct designs for central residential HVAC systems. Therefore, this work investigates the impacts of various pressure duct designs on factors influencing central residential HVAC energy consumption and uses a combination of energy modeling and life cycle cost analysis to simulate the net life cycle impacts of lower pressure duct designs in residences.

2. Background

The energy impacts of varied external static pressures can be categorized generally into (1) direct power draw requirements of the AHU fan, and (2) more complex and indirect relationships between pressure, airflow, delivered sensible and latent capacities, system runtimes, and heat transfer across ductwork surfaces (if ductwork is installed in unconditioned spaces). For direct energy impacts, the fan power draw requirements of any AHU blower are

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determined by system pressure, airflow rates, and fan and motor efficiencies as shown in Eq. (1).

$$W_{fan} = \frac{\Delta P_{system} Q_{fan}}{\eta_{fan}\eta_{motor}} \quad (1)$$

where W_{fan} = power draw of the fan (W); ΔP_{system} = external system pressure (Pa); Q_{fan} = airflow rate ($m^3\ s^{-1}$); η_{fan} = efficiency of the fan (−); and η_{motor} = the efficiency of the fan motor (−). Depending on the type of blower motor used, the airflow rate (Q_{fan}) and the overall efficiency ($\eta_{fan} \times \eta_{motor}$) will respond differently to a specific external static pressure (ΔP_{system}) and thus will have different impacts on fan power draw.

Permanent split capacitor (PSC) motors have traditionally been the most widely used technology in residential AHU blowers in the U.S. with a market share of approximately 90% as of 2002 [14], although the share has decreased some in recent years. PSC blowers do not incorporate controls to maintain airflow rates at constant rates. Therefore, when excess system pressures are introduced, airflow rates typically decrease [7,8,11]. For most parts along the fan curve, increasing the external static pressure and decreasing airflow rates will reduce the power draw of a PSC blower, although the direction and magnitude of changes in fan power draw also depend on the location along the fan efficiency curve [7].

The overall energy impacts of reduced airflows are more complex. Reducing system airflow rates in systems with PSC blowers will decrease the cooling capacity of vapor compression air-conditioning systems, although changes in sensible and latent capacity are typically nonlinear with flow reductions [11,15]. Decreased sensible capacity will lead to increased energy consumption for space conditioning by increasing the length of system runtime, although very few measurements of these impacts have been made in actual homes. Capturing these effects is important; because the power draw of outdoor compressor-condenser units is typically much larger than the power draw of AHU fans [7,8], even a small increase in system runtime may overwhelm any savings in fan power draw. Complicating things further, reduced airflow rates have also been shown to reduce compressor power draw [11,15], which may offset some of the energy impacts of increased runtimes, depending on the magnitude of each change. For heat pumps, lower airflow rates will generally decrease both heating and cooling capacity as well, although the power draw of outdoor units will typically increase [16].

Electronically commutated motors (ECMs), also known as brushless permanent magnet motors (BPMs), utilize variable speed motors and drives that are designed to maintain constant or near-constant airflow rates across a wide range of external static pressures [17]. ECM blowers typically also have a much higher electric conversion efficiency than PSC blowers across a wider range of airflow rates [3,18–20]. In these systems, an increase in system pressure will generally result in an increase in fan power draw and thus fan energy consumption in order to maintain the same (or nearly the same) airflow rate [21], depending on the sophistication of control systems utilized [22]. The absolute magnitude of power draw will still usually be lower than a PSC motor because of typically higher efficiencies at most airflow rates, depending on the magnitude of the pressure increase. Because ECM blowers adjust to maintain airflow rates, altering duct system pressures will not drastically impact indirect energy consumption by altering system runtimes; energy impacts are primarily derived from direct fan power impacts. However, overall space conditioning energy impacts can still be more complex and may vary by climate. For example, at higher fan power draws at higher pressures, more excess heat will be rejected into the airstream, which may increase cooling energy requirements but may also decrease heating energy requirements [23].

Given the complexity of these relationships between external static pressure, airflow rates, fan power draws, fan efficiencies, sensible and latent capacities, system runtimes, and the combined impacts on space conditioning energy consumption, we have conducted a modeling effort to explore the overall impacts on energy consumption and life cycle costs of various duct designs in two typical single-family homes in both hot and cold U.S. climates: Chicago, IL, and Austin, TX. Three external static pressures (ΔP_{system}) were initially specified as design targets (low, medium, and high) in each home and independent HVAC contractors provided ductwork designs and cost estimates for each duct system in each home as if they were to actually perform the design and installation. Details of the duct designs and system configurations (including two types of ductwork materials, rigid and flex) at the various external pressures were combined with typical fan and system curves for air-handling equipment to provide inputs for whole building energy analysis in order to explore these complex relationships in the two model homes.

3. Methodology

The following sections describe the selection of model homes; determinations of inputs for target system pressures, airflow rates, and fan power draws; estimation of duct UA values from the contractors' designs; the energy simulation procedures; and methods for conducting life cycle cost analyses. More details are described in the full project report [24].

3.1. Model home selection

House plans for (i) a typical one-story single-family home with an unconditioned basement in the Midwestern U.S. (Chicago, IL) and (ii) a typical one-story slab-on-grade single-family home in the Southern U.S. (Austin, TX) were first identified by an independent residential HVAC contractor in each location. The homes were designed to meet or exceed most minimum energy code requirements in both locations according to the 2009 International Energy Conservation Code (IECC). Relevant building characteristics are described in detail in Table 1. These homes are considered to be generally consistent with new residential construction practices in each location.

3.2. Pressure, airflow, and fan power determinations

The smaller Chicago home was chosen to have a nominal airflow rate of 2040 $m^3\ h^{-1}$ with ducts installed in the unconditioned basement and the larger Austin home had a nominal airflow rate of 2720 $m^3\ h^{-1}$ with ducts installed in the unconditioned attic. We then specified a range of three target external static pressures (ΔP_{system}) to explore based on the size of each system, defined as "low," "medium," and "high" static pressures herein. These pressures were chosen to accurately reflect a wide, albeit realistic, range observed in real homes in the field and to represent the total pressure introduced by a combination of ductwork, coils, filters, supply registers, and return grilles. Table 2 summarizes the total external static pressures associated with each targeted design: 125, 200, and 275 Pa were used as the low, medium, and high pressures in the Chicago home and 138, 213, and 288 Pa were used in the larger Austin home. Table 2 also shows the external static pressures introduced by ducts alone after assuming 87 Pa is introduced by the combination of filters (25 Pa), coils (40 Pa), and registers, grilles, and dampers (22 Pa). These assumptions are widely used in ACCA Manual D calculations [25]. Although the system pressures identified in Table 2 are higher than standard industry assumptions and test conditions [1], they actually compare very well with existing measurements of pressures in real homes across the U.S. For example,

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