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Modeling the energy and cost impacts of excess static pressure in central forced-air heating and air-conditioning systems in single-family residences in the U.S.

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ABSTRACT

Many central residential forced-air heating and air-conditioning systems contain high pressure drop elements such as high-efficiency or dust-loaded filters, dirty coils, or constricted or undersized ductwork, which are widely assumed to have substantial energy and economic impacts. However, the overall energy and cost consequences of excess static pressures have not been explored in depth across a wide range of climates, homes, or system characteristics. Therefore, we performed 780 annual building energy simulations using BEopt and EnergyPlus to predict the energy and cost impacts of realistic excess static pressures for typical new and existing single-family homes with both permanent split capacitor (PSC) blowers and electronically commutated motors (ECM) in 15 U.S. climate zones. Results demonstrate that excess static pressures can increase annual energy consumption and costs, but the magnitude varies by blower type and climate zone. Moderate increases in static pressures (i.e., from 50 to 150 Pa) were predicted to yield minimal increases in annual space conditioning energy costs (i.e., less than 3% across all homes, blowers, and climates), while more extreme increases in static pressure (i.e., from 50 to 350 Pa) were predicted to yield average increases in energy costs of ~9% with ECM blowers and ~18% with PSC blowers.

1. Introduction

Residential buildings are responsible for over 20% of primary energy consumption in the U.S. and more than 45% of this amount is used for heating and air-conditioning [1]. Over 60% of existing residential buildings and approximately 90% of new residences in the U.S. use central forced-air distribution systems for space conditioning purposes [2]. Additionally, the vast majority of residential buildings in the U.S. are detached single-family dwellings (~70%) [3]. Therefore, central forced-air heating and air-conditioning systems in single-family residences play a crucial role in the energy use and costs attributable to the U.S. building stock. Many central residential heating and air-conditioning systems contain high pressure drop elements such as high-efficiency filters, dust-loaded filters, dirty coils, constricted or undersized ductwork, or closed registers or grilles [4–10]. These excess system pressures are widely assumed to have substantial energy and economic impacts [11–14]. However, the overall energy and cost consequences of excess static pressures have not been explored in depth across a wide range of climates, homes, or system characteristics.

The energy impacts of high static pressures are highly dependent on both the type of blower motor used in the air handling unit and the magnitude of excess static pressure [9,12,13,15]. Two types of blower motors are most commonly used in residential forced-air systems: permanent split capacitor (PSC) motors and electronically commutated motors (ECM) [16]. These blower motors respond differently to increases in static pressures. In a system with a PSC blower, an increase in static pressure will typically lead to a decrease in the airflow rate, often a reduction in fan power draw (depending on the operating point on both the system and fan curves), a decrease in delivered sensible and latent capacity, and an increase in system runtime, which, if large enough, will also lead to an increase in total energy consumption [9].

Conversely, in a system with an ECM blower, which uses a combination of a brushless permanent magnet (BPM) motor and electronic converter to achieve variable speed operation [16], the fan speed will typically increase in order to maintain a relatively constant airflow rate and thus increase fan power draw while

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keeping sensible capacity, latent capacity, and system runtime relatively constant. The overall energy impacts depend largely on the increase in fan power and, to a lesser extent, the amount of excess heat rejected into the airstream. ECM blowers also tend to have higher efficiency and lower power draw than PSC blowers at most static pressures, and thus typically have lower power draw at most operating points [9]. As of 2002, approximately 90% of residential air handling units utilized PSC motors [17], although the share has decreased in recent years with the use of ECM blowers in newer equipment in both new construction and replacements in older homes [18–22].

Standard air-conditioning and heat pump test procedures assume that air handling units and fans are subject to relatively low external static pressures ranging from 25 to 50 Pa in the absence of coil pressure drop or between 75 and 125 Pa including the coil pressure drop, depending on the nominal capacity of the unit [5,23,24]. However, several field studies have demonstrated that most residential systems typically face much higher pressures. For example, in a study of 31 homes in Wisconsin, Pigg and Talerico (2004) measured total static pressures ranging from ~60 Pa to at least 250 Pa [25]. In a study of 60 new homes in California, Wilcox et al. (2006) measured total static pressures during periods of cooling operation ranging from ~75 Pa to as high as ~300 Pa [26]. Most recently, Proctor et al. (2011) measured total static pressures in 80 new homes in California ranging from approximately 130 Pa to over 300 Pa, with the average near ~215 Pa [10]. Similarly high static pressures have also been documented in other recent studies [5–8,27].

Although the magnitudes of excess static pressures in central residential forced-air heating and cooling systems have been well documented, the overall energy and cost consequences have not been explored in depth across a large number of climates, homes, or system characteristics. Therefore, in this work we performed whole building energy simulations using a combination of BEopt [28] and EnergyPlus [29] to predict the annual energy and cost impacts of a wide range of realistic static pressure conditions for two typical vintages of single-family homes (each with both ECM and PSC blowers) in 15 U.S. climate zones. Thirteen external static pressures were chosen to model in each location and home type, increasing from a low of 50 Pa as the baseline static pressure drop to as high as 350 Pa, corresponding to the range of realistic values observed in the literature. A total of 780 individual scenarios were modeled across the matrix of four home types, 15 climate zones, and 13 static pressure conditions.

2. Methodology

The next sections describe the characteristics of the case study model homes and geographic locations (Section 2.1); determinations of inputs for system static pressures, airflow rates, fan power draws, and heating and cooling capacities (Section 2.2); and the energy simulation procedures (Section 2.3).

2.1. Selection of model homes and geographic locations

Fifteen cities were selected to represent all major U.S. climate zones with a wide variety of heating degree days (HDD) and cooling degree days (CDD) [30], as shown in Table 1. Energy prices were assigned to each location based on state-level averages of annual retail electricity and natural gas prices for residential customers in 2013, which were gathered from the US EIA's Electricity Data Browser [31] and Natural Gas Summary [32], respectively.

Two types of homes were selected for modeling in each of the 15 cities: (1) a typical modern high-efficiency home, and (2) a typical existing, slightly older, less efficient home. These home vintages were intentionally chosen to capture a range of envelope characteristics, air-conditioner and furnace capacities and efficiencies, and heating and air-conditioning system runtimes. In all climate zones, the same basic home geometry and heating and cooling system types were used, although assumptions for building envelope characteristics varied by location and vintage. The model home is a 188 m^2 single-family home with three bedrooms, two bathrooms, 2.4 m high ceilings, a natural gas furnace, and a central forced-air air-conditioning system. The selection of specific home characteristics is described in the next sections for each home type.

2.1.1. Modern high-efficiency home

The typical modern high-efficiency home was designed to meet or exceed 2009 International Energy Conservation Code (IECC) requirements in all 15 climate zones [30]. The modern high-efficiency homes were modeled with relatively high airtightness (3 ACH_{50}) in all locations. A detailed summary of all climate-specific characteristics for new homes is shown in Table 2. Walls were wood-framed with fiberglass batt insulation installed between studs 0.4 m on center in either 5 cm × 10 cm cavities (for RSI-2.29 m^2K/W walls) or 5 cm × 15 cm cavities (for RSI-3.70 m^2K/W walls), depending on location. Fiberglass batts were also modeled in the ceiling, with *R*-values dependent on climate zone. All windows were modeled as air-filled double-pane glazing with nonmetal frames, with low-gain (SHGC = 0.3) and low-e glazing. Window areas were set to 4, 8, 4, and 4 m^2 for front, back, left, and right facades, respectively (corresponding to window-to-wall ratios of approximately 12%, 24%, 12%, and 12%). Window *U*-values varied by location. Foundation types varied between crawlspace, basement, and concrete slab, depending on the most common prevalence in each location according to the US Census Bureau [33]. All homes faced north and had a vented attic.

Supplemental mechanical ventilation systems were modeled in the new homes either as direct outdoor air supply systems (in mixed climates) or as energy recovery ventilators (ERVs) with 72% sensible recovery efficiency (in climates with extreme winters or summers). The new homes were also modeled with properly sized high-efficiency heating and air-conditioning systems for each climate zone. The efficiency of gas furnaces was modeled as 98% AFUE and the efficiency of 1-stage central DX air-conditioning units was modeled as 16 SEER (13 EER). Initial simulations in BEopt were used to properly size the central air-conditioner and gas furnace in each home, although adjustments were made to select more realistic air-conditioner and furnace sizes in common commercially available increments of nominal capacity (e.g., in increments of 1.77 or 3.53 kW). Insulated ductwork (RSI-1.4 m^2K/W) with 7.5% duct leakage was installed in either the unfinished attic or basement, depending on location. Nominal airflow rates were assigned based on cooling capacity assuming a standard industry recommendation of 193 m^3/h per kW of capacity.

2.1.2. Typical existing home

The typical existing homes were chosen to represent common existing, slightly older, and less efficient homes with moderate building envelope insulation, moderate airtightness (10 ACH_{50}), and larger and less efficient heating and air-conditioning systems for each climate zone based on typical existing home characteristics in each location. A detailed summary of all climate-specific characteristics for the existing model homes is shown in Table 3. Envelope characteristics such as *R*-values of walls, ceilings, and foundations, window *U*-values and SHGC, and window-to-wall areas were taken from two national surveys of existing homes built after 1979 [34,35]. Foundation types varied by location in the same manner as the modern high-efficiency homes. Window areas were set to