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Single and multi-family residential central all-air HVAC system operational characteristics in cooling-dominated climate

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ABSTRACT

189 conditioned residential single-family and multi-family homes in the cooling-dominated climate of Texas were instrumented with home energy management systems (HEMS) to collect sub-metered data on HVAC operations. This study analyses the HVAC operation from these homes over a 1-year period to determine the duty cycles of the HVAC systems. This includes annual, monthly, and hourly HVAC ON-OFF operation patterns. Regression analysis was used to determine the relationship to HVAC energy use and whole-home energy use, and the influence of building and occupant characteristics. HVAC runtimes are found to be approximately 20% per year, but vary, depending on the season and time of day. Daily and monthly runtime fractions are lowest (10%) at average outdoor temperatures of 15°C, and increase with increasing or decreasing temperature. Hourly runtime peaks at 7 pm in the cooling season, while in the heating and transition seasons, it peaks at 7 am. The number of occupants and the indoor cooling set point temperature were found to most strongly influence the HVAC runtime. The results are formatted to be used in various building and indoor air quality applications where the studied phenomena are influenced by HVAC operation.

1. Introduction

In the United States people spend 68% of their time in residential buildings [1] and 90% of their time indoors [2]. Therefore, there is a need for residential buildings and their systems to provide a comfortable and healthy indoor environment. This is often accomplished through the use of heating, ventilation, and air conditioning (HVAC) systems, particularly in the summer (cooling) and winter (heating) seasons. Nearly 87% of homes in the United States use air conditioning, including 89% of single family homes, and 84% of multi-family homes [3]. In more extreme hot climates such as Texas, air conditioning penetration is nearly 100%. Air conditioning penetration is lower in many other parts of the world, but is predicted to grow worldwide by 72% between 2000 and 2100, particularly in the face of predicted climate change [4]. Nearly all homes in the U.S. (97%) [3] also use central heating. Worldwide, the use of central heating is also predicted to increase by 34% by 2100. Since HVAC systems impact energy use, thermal comfort and indoor air quality, it is important to understand how and when these systems operate. However, there is limited information available on the operational characteristics, and specifically on runtimes of these HVAC systems, particularly in the United States.

A residential centralized all-air HVAC system typical of U.S. homes cycles ON and OFF to maintain a temperature set by a central thermostat. Of homes that utilize HVAC system in the U.S., 80% of single family homes (53 million housing units), and 60% of multi-family homes (13 million housing units) utilize this type of system [3]. Of the homes located in hot and humid climates, as defined by the Building America climate guidelines [5], 82% (15 million housing units) utilize central all-air HVAC, the highest percent penetration of all climate zones in the United States. HVAC use is greatest in the summer (cooling season) and winter (heating season) months, or when indoor and outdoor temperatures have the greatest temperature differential. This runtime fraction, also called duty cycle, or the percent of time the HVAC system is ON, affects both the energy demand on the electric grid, and the other duties of HVAC systems including dehumidification, filtration and, in some cases ventilation [6].

Impact of runtime fraction on energy systems: HVAC use has a large impact on both overall electricity use, and peak demand on the electric grid [7]. Of the 22% of energy use and 38% of electricity use attributed to residential buildings in the U.S. [8], HVAC systems make up over 52% of this energy use, and 31% of this electricity use [9]. These percentages are greater in the more extreme climate regions. In hot climates such as Texas, HVAC use accounts for

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over 56% of electricity use of residential buildings in the summer months [10]. Higher runtime fractions of HVAC systems also equate to greater demand on the electric grid. In the summer (cooling season), particularly in warm climates, in the afternoon and evening hours when residential HVAC use is highest across all homes, a greater duty cycle equates to greater loads on the electric grid. The reason for this is a greater percentage of air conditioning units that are running simultaneously. With the development of demand response programs, dynamic and time-of-use pricing, introduced to reduce load on the electric grid during peak use times [11], it is crucial to understand existing runtime fractions of homes. This will enable better prediction of the effects these programs will have on peak electricity demand and better forecasting of energy demand and use trends.

Impact of runtime fraction on the indoor environment: Regarding the indoor environment, the HVAC system operation directly influences building indoor temperatures, relative humidity (RH), ventilation and recirculation rates, air speeds, and building pressure relative to the outdoor environment. Without heating and cooling, the indoor unit central fan may also provide whole-home air recirculation or ventilation. Air recirculation facilitates air movement and mixing. Most all-air residential HVAC systems only recirculate the indoor air (no fresh air is added), and ideally the return air volume (m^3/s) is equal to the supply air volume. In this case the HVAC system does not change the indoor-to-outdoor pressure. However, even small differences in supply and return air flow rates caused by leaks in supply or return ducts cause that pressure are positively or negatively pressurized affecting the ventilation rate by infiltration. Thus frequency and duration of HVAC system operation may also have a significant impact on ventilation rates in buildings. In newer homes with a tighter building envelope, a forced ventilation system may be installed which provides additional fresh air indoors by adhering to a minimum ventilation rate, as discussed in ASHRAE Standard 62.2 [12]. This is accomplished either through the use of an exhaust ventilation system which depressurizes a home by pushing indoor air outdoors through a vent, or a supply ventilation system which pressurizes a home though the intake of fresh air into the home. Often these ventilation systems are tied to the operation of the main HVAC system and the intensity of this mechanical ventilation depends on the frequency and duration of HVAC system operation.

Air movement, pressure, temperature and RH resulting from HVAC operation also have implications in particulate matter concentrations and indoor chemistry. This includes devices in a home to aid in the removal of pollutants, such as filters installed in the HVAC indoor unit that remove pollutants from the indoor air such as particles and ozone [13–16]. Their effectiveness in removing pollutants depends in part on how often and how much air is flowing through these filters. HVAC operation also affects indoor air flows and mixing conditions, which can result in changes in deposition on indoor surfaces [17–19] and occupants [20,21], and the formation of secondary pollutants [22,23]. Passive removal materials (PRMs) [24–27] and stand-alone air filter effectiveness [23] are also affected by air speed and indoor air mixing from HVAC operation schedules. Indoor concentrations of particulate matter, ozone, secondary organic aerosols and other byproducts have been linked to human health, as discussed in [28–30], thus additional study and analysis on HVAC runtime characteristics is needed to realistically evaluate the dynamics of pollutant concentration and human exposure.

Considering the efforts to improve energy efficiency and reduce peak power consumption, while providing indoor environmental control, researchers use runtime fraction information for various analyses. However, there is very limited information available on runtime characteristics of central all-air HVAC systems. Previous studies that have required HVAC runtime fractions for assessment of indoor pollutant level and human exposure, have assumed or estimated these values, or used energy modeling to determine them [27,31–34]. Several small-scale studies have also been conducted on residential buildings to determine runtime fractions. Previous field studies include the study of 37 homes in North Carolina, 17 homes in Florida, and 17 homes and light commercial buildings in Texas [35–38]. These previous studies have collected data on runtime fractions of a small number of homes, and most for a time period of less than a year. There are also no known studies to date that provide runtime characteristics of multi-family housing. As discussed by El Orch et al. [39] additional information is needed to better characterize runtime fractions in residential buildings. This is particularly important for the hot and humid climate zone which has the greatest percent use of this type of HVAC system in residential buildings.

This research aims to identify annual, monthly, daily and hourly seasonal operation trends from data analysis of HVAC energy monitoring data from 189 homes in a hot and humid, cooling-dominated climate. This includes determining the air conditioning and heating runtime fractions of conditioned residential buildings, including single family and multi-family homes with heat pumps and with air conditioners/gas-fired furnaces. The results are divided into sections by time interval frequency including annual, monthly and seasonally hourly runtime data. A second section covers runtime fractions of indoor fan-only operation. The third section identifies trends in HVAC runtime fractions as a function of outdoor temperature to extend the use of this data beyond the hot and humid climate where this study was conducted. This work highlights the importance of the time-varying and outdoor temperature-varying runtime fractions and the implications this has on the indoor environment.

2. Methodology

The operation of the air conditioning and heating systems was monitored for 189 households in Austin, TX between September 2013 and August 2014. Of the monitored homes, 161 are single family homes, and 28 are multi-family apartments. In all cases the homes utilized a centralized HVAC system, including an outdoor condenser/compressor unit, and an indoor air handling unit. The HVAC is controlled by a thermostat which can be set to heating or cooling mode by the occupant. The results of a survey of a portion of the participating households ($n = 128$) describe the general characteristics of the single family homes (Table 1). Average data for the participating multi-family home properties is also provided in Table 1. The majority of the single family homes studied (86%) are heated using gas heat, while all multi-family homes utilize heat pumps, with the only major differentiating factor between heat pumps and air conditioning/gas heat being the type of heat used. The age of the HVAC system is known for only a limited number of homes ($n = 12$). However, assuming a new HVAC system was installed and has not yet been replaced in homes with known dates of construction built in the last 10 years, the average age of these HVAC systems is 6.9 years. The average indoor cooling and heating set point temperatures of the single family homes have a standard deviation of 1.8 °C and 1.7 °C respectively across the reporting homes ($n = 103$), with the average maximum setback of 1.8 °C higher and 2.0 °C lower, respectively. 28% and 29%, respectively, reported a constant set point temperatures in the cooling (summer) and heating (winter) seasons. Indoor set point temperatures were not available for the studied multi-family homes.

Twenty-two of the homes utilize timed whole-home ventilation systems, all of which are single family homes. All homes studied pay for their utility bills. The electricity and gas utilities utilize a tiered rate structure that increase in price by total cumulative use