Energy and Buildings 135 (2017) 166–175

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Characterizing variations in variable air volume system controls

Xiufeng Pang*, Mary A. Piette, Nan Zhou

Lawrence Berkeley National Laboratory, United States

ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 13 October 2016
Accepted 16 November 2016
Available online 19 November 2016

Keywords:
Variable air volume (VAV) system
Controls
EnergyPlus
Building energy performance
Building simulation

ABSTRACT

The variable air volume (VAV) system is the most popular form of heating, ventilation, and air-conditioning (HVAC) system used in commercial buildings. Researchers and engineers often use VAV systems as a reference when evaluating new technologies and systems or comparing design options. However, VAV system performance varies significantly, in part because of variations among VAV system controls, so, when analyzing use cases, it is critical to accurately represent system controls in order to accurately define system performance. Unfortunately, no existing literature documents standard VAV system controls for this purpose. This paper aims to remedy this omission by characterizing the variations in VAV system controls and proposing an approach to representing VAV system baseline performance. We used EnergyPlus to model variation among VAV system controls. We use the medium-size office reference-building model developed by the U.S. Department of Energy to demonstrate the impact of variations among controls in two U.S. climate zones and sort system performance into “good,” “average,” and “poor” categories.

1. Introduction

A single-duct variable air volume (VAV) system controls temperature in a space by varying the amount of supply air, as shown in Fig. 1 [1]. Single-duct VAV systems use one of three types of terminal units: a VAV box with or without reheat coil, or a fan-powered VAV box and induction unit. These terminal units can also be categorized as pressure-dependent or pressure-independent. A pressure-dependent terminal unit controls air damper position in response to room air temperature, and airflow may increase or decrease as the upstream duct pressure varies. A pressure-independent terminal unit controls actual supply airflow through an airflow measuring device incorporated in the terminal unit, and the position of the air damper is adjusted to maintain an airflow set point in response to room air temperature. VAV system heating and cooling are provided either by a central plant or local equipment. This study focuses on VAV systems with pressure-independent VAV boxes and reheat coils.

To maintain a comfortable indoor environment, heating, ventilation and air-conditioning (HVAC) system operation is regulated to maintain a list of control-variable set points. The controls discussed in this paper refer to control sequences used to determine the values of these HVAC system set points and their associated control parameters, as well as to start or stop the equipment.

VAV systems are commonly used in large commercial buildings and considered as the most energy efficient systems in use today [2]. Therefore, researchers and engineers often use VAV systems as reference cases when developing new HVAC technologies and optimizing designs. Yao et al. [3] compared VAV systems, CAV systems and fan-coil systems, in a small office building for six different cities in China. Their simulation results showed that VAV systems can produce 17.0–37.6% energy savings when compared to the CAV systems, and 4.6–10.2% energy savings when compared to the fan-coil systems, depending on the climate. Zhou et al. [4] compared the energy performance of a variable refrigerant flow (VRF) air conditioning system with that of a VAV system. Simulation results showed that the VRF system achieved 22.2% energy savings compared with the VAV system. Aynur [5] conducted a similar comparative study between the VRF system and the VAV system and reported that the VRF system promised 27.1%–57.9% energy savings potentials when compared to the VAV system. Sastry and Rumsey [6] conducted a side-by-side comparison between a VAV system and a radiant cooling system in an office building in Hyderabad, India. The office building uses two cooling systems. Half of it has a VAV system and the other half has a radiant cooling system with dedicated outdoor air system (DOAS). After two years of operation, the radiant system has used 34% less energy as compared to the VAV system.

* Corresponding author.
E-mail address: xpang@lbl.gov (X. Pang).

http://dx.doi.org/10.1016/j.enbuild.2016.11.031

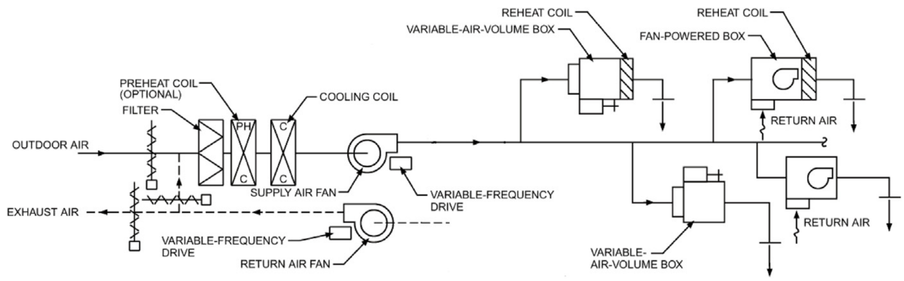

Fig. 1. Single-duct VAV system with different types of terminal units.
Source: ASHRAE Handbook – HVAC Systems and Equipment 2012.

However, the energy performance of a VAV system highly depends on the controls [7–13]. If VAV systems are used as a reference, it is critical to specify a set of control sequences that is used to establish the baseline that allows for meaningful comparisons. Any conclusion drawn from a comparison to a VAV system for which the system controls have not been explicitly defined is limited and can be misleading. Unfortunately, VAV system controls were not explicitly defined in any of the cited studies.

Our study characterizes the variations among VAV system controls and proposes an approach to defining baseline VAV system performance for different use cases. We characterize controls according to system performance as "good," "average," or "poor." Good practices are defined mainly based on [14–16]. Average and poor practices are based on expert opinions from building commissioning practitioners and researchers. We use the U.S. Department of Energy medium-size office reference-building model [17] to illustrate the impact on system energy performance of variation in VAV system controls.

2. Controls and their variations

Table 1 shows a common list of control variables and summarizes the range of controls. These controls are described in more detail below and are based on a conventional VAV system with direct digit control (DDC) devices, as shown in Fig. 1. Some advanced features or components, e.g. airflow stations and heat-recovery wheels, are not included in this study.

2.1. Occupied room set-point temperatures

The DDC controller of a VAV box has two set-point temperatures, one for cooling and one for heating, which affect the operation of the box. The "occupied cooling set-point temperature" is the temperature in the space during occupied hours when cooling is required. The "heating set-point temperature" is the temperature in the space during occupied hours when heating is required. The cooling set-point temperature should be set higher than the heating set-point temperature to avoid rapid switching between cooling and heating operations. The difference between the cooling set-point temperature and the heating set-point temperature is referred to as the "deadband," within which the VAV box will take no action related to the damper and reheat valve. That is, the damper will remain at the minimum position to maintain the minimum airflow set point, and the reheat valve will remain closed. The "unoccupied set-point temperature" is discussed below in the "night setback" section.

Many local governments and other institutions in the U.S. mandate space temperature set points in their sustainability and energy-efficiency policies. A range of the set-point temperatures is reported from 20 °C (68 °F) to 25.6 °C (78 °F) [18–23], adapted from American National Standards Institute (ANSI)/American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55–2004 and 2010 [24]. The U.S. Occupational Safety and Health Administration recommends a range of 20 °C (68 °F) to 24.4 °C (76 °F) [25]. Based on the information above as well as interviews with facility managers, we chose a range of 21.1 °C (70 °F) to 23.3 °C (74 °F) to represent "average" cooling and heating set points, respectively, in U.S. office buildings. We categorize a cooling set point of 24.4 °C (76 °F) and a heating set point of 20 °C (68 °F) as "good" practice. We define "poor" practice as 22.2 °C (72 °F) for both cooling and heating set points. Specific regions might choose a different range of set-point temperatures based on local policies and practices.

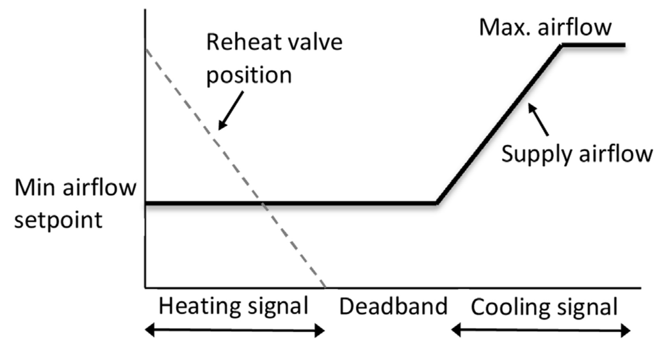

Fig. 2. Single maximum control diagram.

2.2. Night setback

Since 1999, ASHRAE Standard 90.1 [26] has mandated setback controls. Night setbacks reduce heating and cooling set-point temperatures when a building is unoccupied or during other periods when these temperatures are accepTable Setbacks avoid waste of energy during hours when the building is unoccupied. It allows the HVAC system to automatically restart and operate temporarily during off-hours to maintain the setback temperature and thereby prevent spaces from becoming so hot or cold.

We determined the ranges of "good," "average," and "poor" setback temperatures for unoccupied buildings based on research results [27,28] and good industry practices. "Average" setback temperatures were determined to be 15.6 °C (60 °F) and 29.4 °C (85 °F) for heating and cooling, respectively, "good" temperatures were 12.8 °C (55 °F) and 32.2 °C (90 °F) and "poor" temperatures were 18.3 °C (65 °F) and 26.7 °C (80 °F).

2.3. VAV box minimum airflow

VAV boxes with reheat coils are typically controlled using single maximum control logic, shown in Fig. 2 [29,30]. Supply airflow is adjusted between maximum and minimum values in response to a cooling signal. The minimum airflow rate is maintained as the space temperature falls through the deadband into heating mode. The reheat valve then opens to maintain the space at the heat-