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Model-based space temperature cascade control for constant air volume air-conditioning system

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ABSTRACT

Constant air volume (CAV) air-conditioning system is still widely used for cooling/heating buildings because of the requirement of air changes in many occasions and its simple system design as well as low primary cost. The space temperature of the CAV air-conditioning system is usually controlled by using conventional proportional-integral (PI) control algorithm, which tracks the space temperature by regulating the opening of the water valve directly. However, the control performance of the space temperature is usually unsatisfactory because of the significant thermal inertia of the building mass and the large volume of the indoor air. This paper proposes a model-based cascade control method for the space temperature control of the CAV system aiming to improve the control robustness and accuracy. A supply air temperature prediction model is developed to predict the system demand supply air temperature based on the real-time load condition and space temperature. The prediction is used as the set-point, and the space temperature is well controlled by regulating the water valve opening. The proposed control method was validated in a simulation CAV system as well as on an experimental platform. The validation results show that the proposed model-based cascade control method achieves better space temperature control performance than the conventional PI control. This control method may well track the space temperature directly both in the virtual CAV system and the real experimental system.

1. Introduction

Air-conditioning system is mainly used to provide a comfortable indoor environment for buildings, which consumes more than 40% of the energy for buildings [1,2]). However, the indoor environment is not really good in many buildings [3]. One difficulty in optimizing the indoor environment is due to the actual controls, which are far from ideal in terms of their ability to react and anticipate to disturbances or uncertainties in the indoor environment [4,5]. Therefore, to improve the control performance of the indoor environment by using an advance control strategy is also a way to improve the efficiency of energy utilization.

Air-handling unit (AHU) as a typical device of the air-conditioning system is widely equipped to treat the supply air for maintaining a desired indoor environment. There are two basic types of AHU, i.e., constant air volume (CAV) and variable air volume (VAV) [6]. For a CAV system, the air volume is constant, and the fan and dampers are not regulated. For a VAV system, the air volume is variable by regulating the fan speed or dampers. Both in CAV system and VAV system, the mixed air of outside fresh air and return air is driven by a supply air fan through the AHU. The air will be cooled down or heated up in the AHU by the water flow inside the cooling/heating coil. The cooled/heated supply air is then delivered to indoor spaces, and the space environment regulation of the air-conditioning area is realized. VAV air-conditioning system generally changes the volume of supply air so that the cold air sent to the air-conditioning area always meets the load demand, and the supply air temperature is controlled at its set-point by regulating the water flow rate inside the cooling/heating coil. However, CAV air-conditioning system keeps the supply air volume constant and meets cooling demand of the air-conditioning area by changing the water flow rate inside the cooling/heating coil, and the supply air temperature is not controlled.

In the air-conditioning system, the heat exchange occurs between the water flow and the air flow. The dynamics of a heat exchanger is generally described by a partial differential equation [7]. Therefore, a typical air-conditioning system is an infinite dimensional dynamical system, which makes it difficult to implement the control theories and design techniques developed for lumped systems [8]. The space temperature change is an uncertain and nonlinear dynamic process because of the thermal characteristics of the time-varying operating

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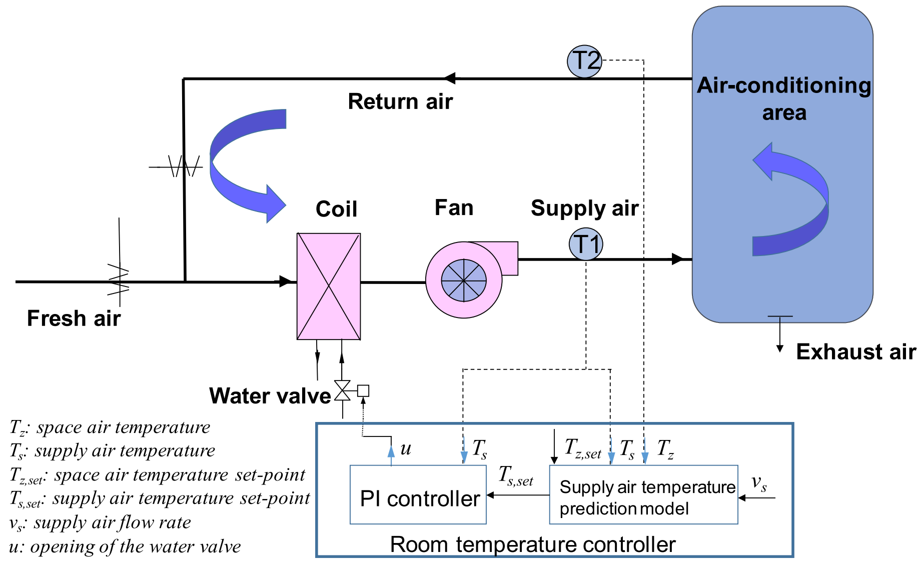

Fig. 1. Schematic diagram of a typical CAV system and its control.

environment [5,9]. That is why the space temperature control in an air-conditioning system is a non-trivial problem [10].

In recent years, the VAV air-conditioning system has become increasingly popular because of its better energy efficiency and regulation performance [6,11]. Aiming at improving the robustness of the space temperature control, researchers developed a number of control strategies for the VAV systems, such as model-based predictive control [12], fuzzy control [13], robust infinite control [14], supervisory control [15], bilinear control [16,17] and many other controls [18].

However, the CAV air-conditioning system is still widely used in practical application because of the requirement of air changes in many occasions and its simple system design as well as low primary cost. In some public buildings such as subway stations and shopping centers, the air change is usually strictly designed in some practical projects, and the fans operate at constant volume. In these CAV air-conditioning system, the space temperature is usually controlled directly by using the conventional PI control algorithm to regulate the opening of the water valve [6]. The thermal inertia is large in the whole control process. Due to the uncertainties associated with the dynamics, PI controllers cannot always satisfy the control requirement. The control performance of PI controllers varies significantly with the operating conditions due to the lack of appropriate tuning. The controlled loops may become sluggish or oscillatory at certain times [4,5,19]. The poor quality of the temperature control is one of the causes for occupants' dissatisfaction and has been accepted in practice only because of the lack of catastrophic consequences [6,20].

Unlike the VAV air-conditioning systems, there are few advance control methods developed for the space temperature control of the CAV air-conditioning systems. Xu et al. [6] proposed a robust model-based predictive control (RMPC) strategy for the temperature control of an air-conditioning system, which consists of multiple local-loop processes and each process suffers from different dynamics uncertainties or variations. The robust control scheme developed in Huang et al. [21] was used to design the robust controller. A CAV air-conditioning system was used as an example to illustrate and validate the procedure of using this RMPC strategy. Case study showed that the application of RMPC in CAV air-conditioning system can achieve a better set-point tracking of the space temperature and a better disturbance rejection of disturbances when compared with conventionally used PI control. However, there are several control parameters in this control strategy, which are difficult to be obtained in the real building system.

Cascade control is often considered as adaptive and robust type of control method and widely used in the applications where PI controllers are used [22,23]. Phalak and Wang [23] evaluated the performance of the cascade control on the building static pressure in comparison with two conventional controls (i.e., direct pressure control and volume tracking control) by simulation. The results conclude that the cascade control achieves the better stability of the system by reducing the sensitivity to the change in the operating conditions and controller gains. However, this cascade control was designed to control the building pressurization of the VAV air-conditioning system.

This paper proposes a model-based cascade control method for the space temperature control of a CAV air-conditioning system to improve its robustness and accuracy. It is well known that the response of the space temperature is slow. However, the response of the supply air temperature is very quick when the water flow rate inside the cooling/heating coil is changed. In this control method, a supply air temperature prediction model is developed and used to predict the system demand supply air temperature according to the real-time load condition and space temperature. The aim is to transfer the variation of the space temperature and the load to the supply air temperature. The cooling/heating water flow rate just needs to be regulated to track the predicted supply air temperature. By this control method, the response of the control process is more timely, which achieves a more robust and accurate space temperature control.

2. Description of the air-conditioning system and the control method

A typical CAV air-conditioning system is illustrated in Fig. 1, where the supply air flow rate is constant. The supply air consists of the fresh air from outdoor and the returned air from the conditioned space. It is cooled down or heated up by the coil, and then delivered to the air-conditioning area to regulate the space thermal environment. The space air temperature can be controlled by a water valve according to the space temperature measurement and its set point.

Normally, the PI controller is used to track the space temperature directly by regulating the opening of the water valve. It is well known that the air-conditioning includes two important processes. One is the air-handling process in the air handling unit when the air passes through the cooling/heating coil, the other is the air-conditioning process in the room when the supply air is delivered to the indoor space and mixed with the indoor air. It absorbs the heat and moisture of the indoor air, and finally is drawn back. The air-handling process in the air handling unit is a quick response process. However, the air-conditioning process in the room is a slow response process because of