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A coordinated VAV control with integration of heat transfer coefficients for improving energy efficiency and thermal comfort

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Abstract

The indoor temperature in traditional Variable Air Volume (VAV) systems is controlled synchronously by increasing or decreasing the damper of the valve based on the return air temperature. However, the thermal comfort cannot be guaranteed since the load inside may not be evenly distributed, energy is wasted due to continuing cool down space even though no occupants inside. Thus, this paper introduced a coordinated control strategy aiming to improve energy efficiency and thermal comfort of large-scale rooms. A case study was presented on a summer day to show the benefits of the proposed method. The selected chamber is divided into two subzones with each controlled by a separated VAV box. Typically, each zone can be controlled independently by regulating its corresponding VAV box to track the temperature set point. Since occupants may move randomly, the worst scenario is that one subzone was fully packed. In this case, the corresponding representative temperature cannot be cooled down to its set point, and an extra airflow rate may be needed using its neighbor VAV box to cool down the air inside. To achieve this function, the thermal coupling effect between zones is considered with the Heat Transfer Coefficient (HTC) integrated into the control platform established in TRNSYS. The simulation results show the proposed control can deal with the dynamic variation of load distributions inside. The introduction of heat exchange between adjacent zones can improve the accuracy of the temperature controls. The energy consumption of the variable speed supply fans was compared with conventional control, approximately 10% of energy saving was achieved.

Peer-review under responsibility of the scientific committee of the World Engineers Summit – Applied Energy Symposium & Forum: Low Carbon Cities & Urban Energy Joint Conference.

Keywords: Coordinated VAV control, Heat transfer coefficient, thermal comfort, energy efficiency

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1. Introduction

Large-scale rooms, which characterized by large volumes with high height, are widely used in university, government and commercial buildings to provide professional accommodation for lectures, seminars, conferences and other large formal meetings. Uneven load distribution is a very common phenomenon in large-scale rooms due to internal and external thermal conditions. For example, audiences in a large-scale lecture theater would like to sit randomly, and some areas may have a large number of audiences while other areas may have a small number and even none. Currently, the typical control design for VAV air-conditioning system of large-scale rooms configures one thermostat to control a number of VAV boxes based on the measured temperature. This configuration may work well under the condition that the cooling load is evenly distributed all the time and the temperature is identical in the whole space (Lin, Federspiel et al. 2002). However, this condition may not always be true for large-scale rooms since the dynamic variations of occupancy, which leads to a big challenge for the conventional control system. Without properly dealing with the temperature gradient and uneven load distribution, the performance of the temperature control may be deteriorated and simultaneously the energy may be wasted. An average temperature was calculated around a person by CFD and feedback to the ON/OFF controller to realize a local control aims to reduce energy consumption (Alhashme and Ashgriz 2016). The localized airflow control system achieved better energy efficiency, better thermal comfort and separation of contaminants (Lo and Novoselac 2010). Peng (Peng 1996; Peng and Van Paassen 1998) introduced a state-space model based on a zonal model for controlling indoor temperatures in the occupied level. Huang et al. proposed an artificial neural network (ANN) model-based system identification method to model multi-zone buildings by considering the effects of thermal coupling between adjacent zones (Huang, Chen et al. 2015). Yao et al. developed a three-zone state-space room model for studying both the dynamic response of air temperature and humidity in rooms, the heat transfer coefficients, in particular between two adjacent zones, was tried and adjusted based on experiment results (Yao, Yang et al. 2013).

In order to supervise and optimize the operation of air-conditioning systems regarding energy efficiency and thermal comfort, this paper proposes a new temperature control design for large-scale rooms, which can deal with the problem of unevenly distributed load and the frequent change of occupants. The proposed control scheme design divides a large-scale room into some zones, each of which is served by a separate VAV box controlled independently. Only zones with occupants are supplied with cooling air to track the temperature set point. The heat exchange is activated when one of sub-zone cannot cool down to its set point with the full cooling output. A case study of the control strategy is evaluated by commercial software TRNSYS.

2. Methodology

2.1. Proposed control design

Different from the traditional VAV control which controls the whole space synchronously, the proposed control is an independent zonal temperature control by dividing the space into several controlled subzones. Fig. 1 gives the block diagram of the independent control for 2 VAV boxes. It should be noted that there are no physical partitions between the adjacent zones in a real application.

The control strategy includes two parts: Phase I and Phase II control. The detailed control strategy for the proposed temperature model can be found in reference (Zhou, Huang et al. 2014). Phase I control is an individual zonal temperature control, just because each subzone can be controlled to its set point independently by adjusting the airflow rate from its corresponding VAV box. However, the worst scenario is when the load in a subzone reaches its threshold, the corresponding representative temperature cannot be cooled down to its set point; an extra airflow rate is needed using its neighbor VAV box to cool down the air inside, this is Phase II control. Phase II control is achieved by heat exchange channel since the thermal coupling effect starts to take advantage of control. The method to calculate the heat transfer through the heat exchange channels can be found in reference (Zhou, Wang et al. 2017). Here gives the equation of the heat exchange between adjacent zones:

$$\Delta Q_{i,j} = K_{i,j}\left(T_{z,i} - T_{z,j}\right) \tag{1}$$

Where i refers to the i^{th} zone; and j refers to the j^{th} zone; T_z is the zonal temperature; $K_{i,j}$ is heat transfer coefficient, W/K; ΔQ is the heat transfer between the adjacent zones, W. The heat transfer coefficient was set to 3000 W/K in this case.

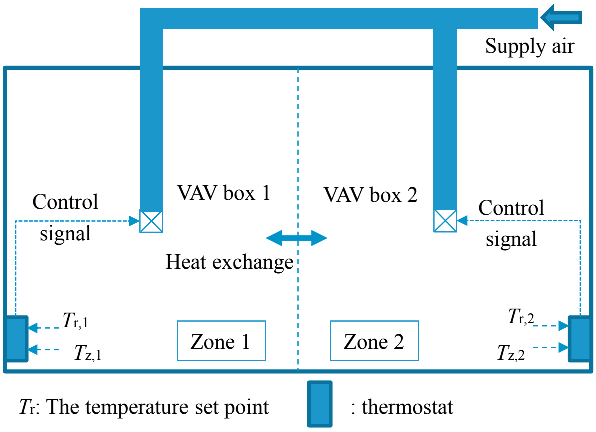

Fig. 1. Block diagram of independent control for 2 VAV boxes

2.2. Control platform description

A zonal temperature control platform was established in TRNSYS to realize the system, see Fig. 2, where its zonal model (Type 56) was used to model the space temperature dynamics of both zones. Two variable speed fans (Type662) were used to control the supply airflow rate (rated flow rate 1780 kg/h) for Zone 1 and Zone 2. The supply air temperature was set to be 17°C. The simulation time starts from 4440 h to 4464 h (a typical summer day in July) with time interval 30 seconds. It was found that the PI controller with P = -0.5 and I = 0.04 can control the space temperature well. It is noted that in TRNSYS, the supply air from Zone 2 cannot directly affect Zone 1 since they are independent of each other, but the introduction of heat exchange channel between them can realize Zone 2 influence Zone 1. The heat exchange can be defined as wall gain (kJ/h) in an internal wall shared by both zones. Here, wall gain represents the energy flowing to the jointly owned wall surface. The control strategy is achieved by an external program in Matlab (type 155).

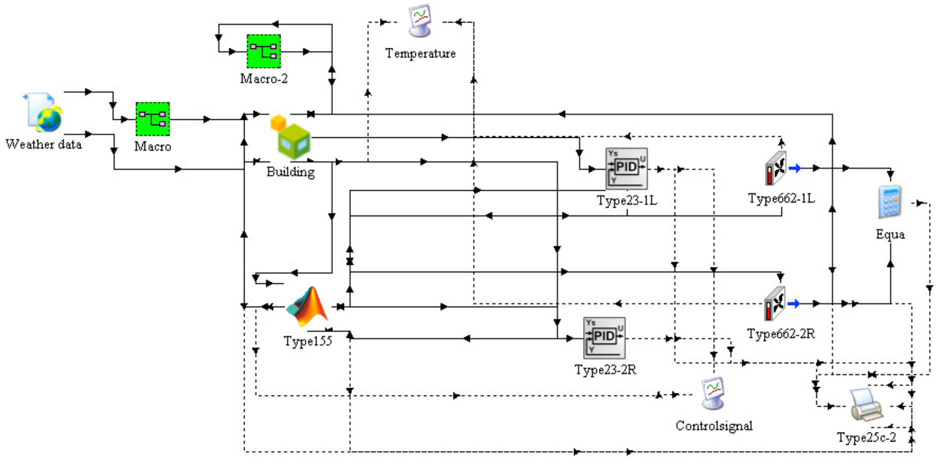

Fig. 2. Control platform with 2 zones in TRNSYS

Here gives an example of how the control strategy works on the control platform. An uneven load distribution was created in both subzones from 4440 h to 4464 h. It is mentioned the cooling load experience a sharp shift from Zone 2 to Zone 1 from 4455 h to 4457 h, as shown in Fig. 3. This is an extreme case to show the superiority of the developed control strategy (usually occupants will move on a small scale in large space rooms). Since the load accumulated in Zone 1 and reached its maximum (5.44 kW) in this period, the corresponding VAV box 1 cannot cool down the temperature to track its set point even though it is fully opened. Thus, the VAV box 2 is switched on and the heat exchange channel is activated to continually cool down the temperature in Zone 1. In the control simulation platform, the idea of the heat transfer channel is equivalent to moving a portion of the load from Zone 1 to Zone 2, so that the supply air in Zone 2 will increase and the temperature in Zone 1 will drop accordingly.

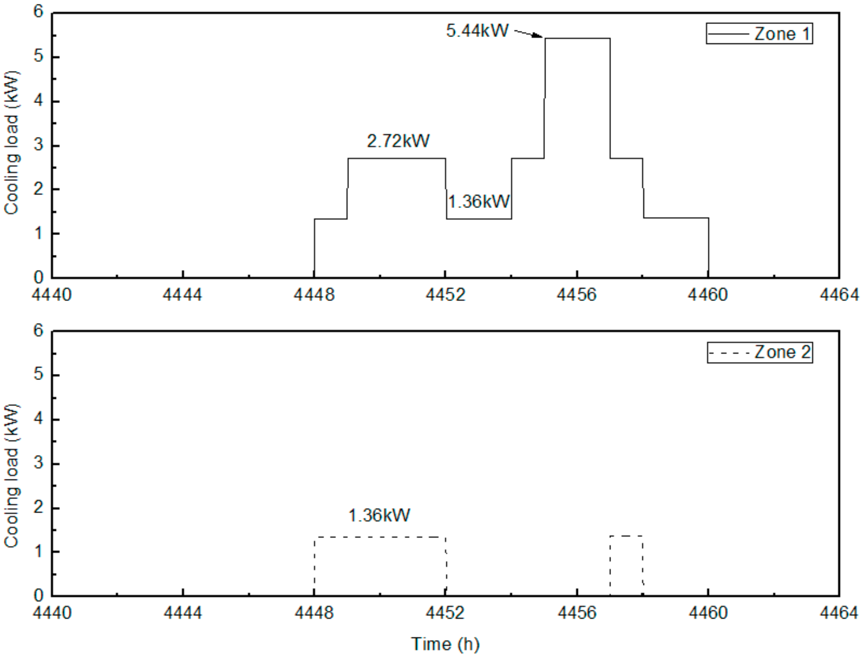

Fig. 3. Load profile for Zone 1 and Zone 2

3. Simulation results

It can be considered as a simple independent temperature control when the heat exchange is not integrated into the control platform. When both Zone 1 and Zone 2 have the same temperature set-point (say 25°C), the temperature variation and the supply airflow rate of Zone 1 and Zone 2 are shown in Fig. 4. Both the temperature and airflow rate experienced a sharp increase or decrease when cooling load started to appear, which is due to the response of the PID controllers. The air conditioning system operated from 4448 h to 4460 h and the fans were switched off (the airflow rate was 0) when there was no cooling load inside. The temperature in both zones can be controlled well except Zone 1 from 4455 h to 4457 h. It was obviously out of control even though the airflow rate reached its rated maximum value: 1780 kg/h. The temperature in Zone 1 reached 26.8°C while Zone 2 could control its temperature accurately. In order to continue to cool down the Zone 1, the heat exchange calculated by Equation (1) was added to the control platform for further considerations.

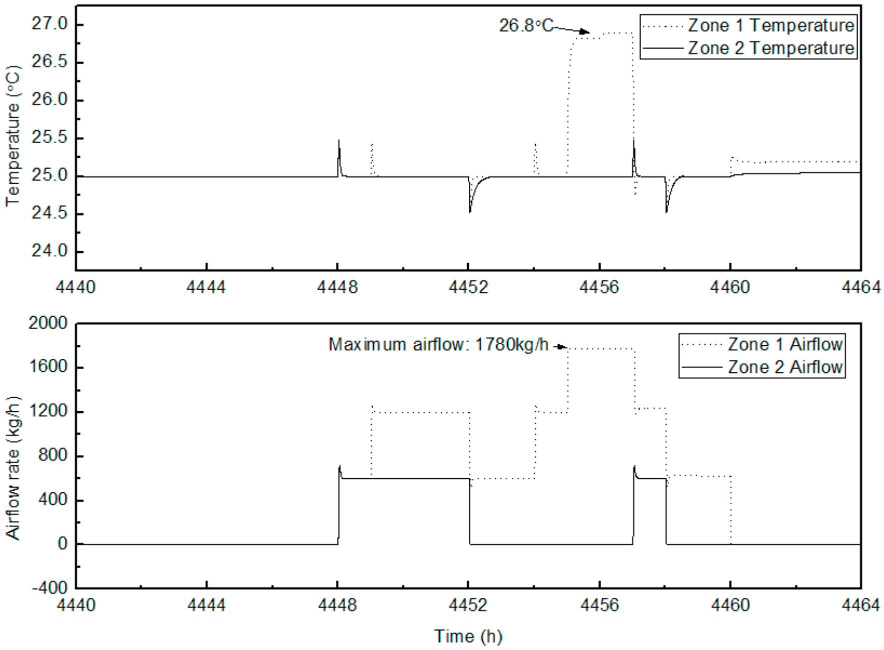

Fig. 4. Temperature and airflow rate control for Zone 1 and Zone 2 without heat exchange

Phase II control stage was activated when Zone 1 was out of control based on the proposed control strategy. Accordingly, the heat exchange channel opened and added to the joint internal wall. Fig. 5 shows the temperature in Zone 1 decreased from 26.8°C to 25.6°C since part of the load was removed from Zone 1 to Zone 2. Consequently, an extra airflow rate (429 kg/h) was implemented into Zone 2 as a result of 2.5% more energy consumption by supply fan compared with simple independent zonal temperature control. The thermal comfort index PMV was improved as the temperature in Zone 1 decreased. However, the fan energy consumption was 30.5 kWh for the proposed control, while the traditional control consumed 33.8 kWh, meaning nearly 10% of energy saving was achieved. The introduction of heat exchange, equivalent to the external disturbance added to the control system, leads to small fluctuations in temperature as well as supply airflow rates, as shown in the Figure. The method presented here shows an extreme case when load is shifting from one zone to another, which is rare in real applications. Thus, the proposed method could control temperature more precisely while taking into account the thermal coupling effect between adjacent zones. It will be essential to optimize the allocation of the supply air in large-scale spaces to deal with the frequent load variations.

4. Conclusion and Discussion

In this paper, we proposed an independent zonal temperature control strategy for large-scale space aiming to (1) deal with the uneven distribution of load; (2) achieve an independent zonal control based on zonal demand; (3) triggered thermal exchange to improve zonal temperature control while one of subzone was out of control. The simulation results show the proposed control can deal with the dynamic variation of load distributions inside. The introduction of heat transfer channel between adjacent zones can improve the accuracy of the temperature controls. The proposed temperature model can be used to develop or investigate the control methods used in a multiple-zone control mode for large-scale spaces. The energy consumption of the variable speed supply fans was compared with conventional control, approximately 10% of energy saving was achieved. Limitation of the controlled strategy is that only two zones were considered in this paper. Besides, the temperature still cannot be controlled exactly to its set point even though the thermal exchange was activated in the control platform.

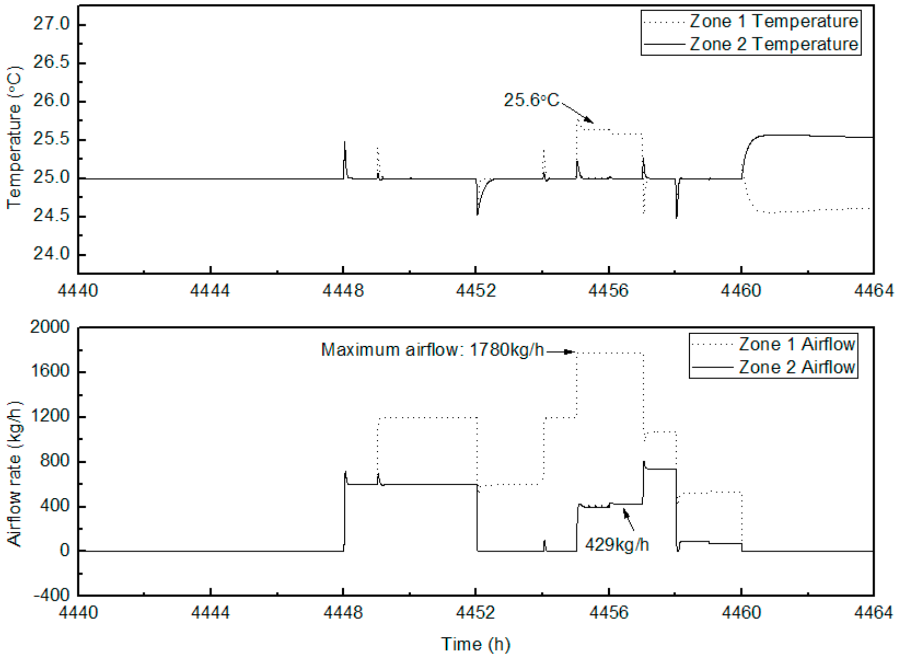

Fig. 5. Temperature and airflow rate control for Zone 1 and Zone 2 with heat exchange

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