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An evaluation of heat transfer coefficient in an independent zonal temperature controls with CFD

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Abstract

This paper introduced a methodology to calculate the heat transfer coefficient between two adjacent air conditioning zones via a virtual wall aims to improve the independent zonal temperature control for a VAV system. The selected room was divided into two subzones with each controlled by 2 square ceiling diffusers mounted on the up-ceiling level. A virtual wall was artificially identified and split into the fluid domain in Fluent. The heat transfer coefficient (HTC) across the virtual wall was derived from the discrete energy equations and obtained by implementing UDFs in the Fluent solver, both the heat transfer due to air mass flows and the heat exchange due to turbulence were considered in the model. A 2-separate VAV control platform was established in TRNSYS and the HTC was fed to the control platform to evaluate the impact of HTC on the temperature control system. The simulation results shown it has an insignificant impact on the controllers, but the temperature on both sides were controlled precisely within the expected range compared with CFD simulation results.

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Keywords: Heat transfer, square ceiling diffuser, virtual wall, Fluent, temperature control

1. Introduction

Large space, such as shopping malls, theaters, sports center, consumes energy heavily, the heating load inside is partially or randomly distributed in most time of the year, thus to condition areas that are non-occupied results in a huge energy waste. Besides, the typical control design configures one thermostat to control a number of VAV boxes based on the measured return air temperature; this consequently leads to over-cooling in the non-occupied area while insufficient cooling in the occupied zone. There are some

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strategies to deal with this problem, such as increase room set-point [1]; deploy multiple sensors to monitor the temperature in occupied level [2-3]; the application of wireless sensors [4-5]. Regarding the control strategy, demand-based temperature control was introduced and energy conservation was achieved by controlling the temperature in occupied level [6]; a zone temperature based demand response control was proposed to alleviate energy use while keeping temperatures within the limits of ASHRAE Standard 55 [7]. However, thermal comfort in occupied level may not be satisfied by increasing room set-point, and it is tough to install temperature sensors precisely in breathing level, the application of wireless sensor is challenged for sampling reliable and stable data from the measurement site.

This paper proposed an independent zonal temperature control strategy for a large space; the core idea is dividing the controlling area into a number of subzones, and each sub-zone is controlled by an independent VAV box. The Computational Fluid Dynamic (CFD) and Energy Simulation Software (TRNSYS) are introduced into this study to realize the control strategy. CFD can be used to obtain the heat transfer coefficient as well as the detailed distribution of temperature inside the room. The energy simulation can be applied to realize a better control of room temperatures. This paper can be organized as follows: a detailed methodology will be introduced in section 2, a CFD case study for calculating the heat transfer coefficient will be illustrated and followed by the simulation results in section 2. A control platform will be addressed in section 3; section 4 gives the conclusion at the end.

2. Methodology

The proposed control strategy combined CFD and energy simulation software together. CFD can be used to obtain the heat flux as well as the detailed distribution of temperature inside the room. The energy simulation software can be applied to realize a better control of room temperatures. Since the air-conditioning space was artificially separated thus a virtual wall was assumed existed between each zone, for simplification, the selected room was divided into only two subzones, as shown in Fig. 1, the virtual wall was treated as the interior in the Fluent fluid domain which the mass and heat exchange can occur via this surface. The heat transfer coefficient (HTC) was derived from the discrete energy equations and obtained by implementing UDFs in the Fluent solver. A 2-separate VAV control platform was established in TRNSYS, and the HTC was fed to the control platform to evaluate the impact of HTC on the temperature control system.

The critical problem is how to find the mass and heat exchange between one zone and another. It can be achieved by zonal model [8]. The pre-condition of the zonal model is the air flow pattern seems constant and time invariant if the conditioning air is supplied at a constant speed, based on this assumption, the air flow field need to be solved only once by CFD simulation, what is the left to be addressed is the energy equation. As shown in Fig.1, the room is divided into zoneL and zoneR, and each sub-zone is considered well mixed and is depicted with one temperature. It is noted here that the border between two adjacent air zones is also the boundary of the grids that located on both sides of the border, the velocities and exchange coefficients of this grid can be used to calculate the mass and heat exchanges between two air zones. Based on the zonal model theory, the heat transfer between two adjacent zones can be written as following equations:

$$a_{R,12} = \sum_{j=1}^{ny}\sum_{k=1}^{nz}\sum_{i=1}^{i_a} C_p \left(\Delta y \Delta z\right)_{i,j,k} \left(D_{R,i,j,k} + \rho MAX\left[-u_{i,j,k}, 0\right]\right) \quad (1)$$

$$a_{L,21} = \sum_{j=1}^{ny}\sum_{k=1}^{nz}\sum_{i=1}^{i_{a+1}} C_p \left(\Delta y \Delta z\right)_{i,j,k} \left(D_{L,i,j,k} + \rho MAX\left[u_{i,j,k}, 0\right]\right) \quad (2)$$

Where a_{R12} is the heat transfer from Right zone to Left zone, $a_{L,21}$ is heat transfer from Left zone to Right zone vice versa, w/K; C_p is specific heat capacity, J/kgK; D is diffusion conductance, kg/m^{2}s; ρ is air density, kg/m^3; $u_{i,j,k}$ is velocity in x positive direction, m/s; i, j, and k is cell index; ny and nz is the total number of cells in Y and Z direction; i_a and i_{a+1} is the first cell index adjacent to the virtual wall as shown in Fig.1. In fact, a_{R12} may not equal to $a_{L,21}$ since the balance between both side of the virtual wall is interrupted by an imbalance of the airflow rates in the left and right zone, that`s the main reason that results in the temperature difference between the two subzones.

Eq. 1 can be rewritten with two separate parts shown in Eq. 3:

$$a_{R,12} = \sum_{j=1}^{ny}\sum_{k=1}^{nz}\sum_{i=1}^{i_a}\left(\Delta y \Delta z\right)_{i,j,k}\frac{k_{eff}}{\left(\delta x\right)_r} + \sum_{j=1}^{ny}\sum_{k=1}^{nz}\sum_{i=1}^{i_a} C_p\left(\Delta y \Delta z\right)_{i,j,k}\rho MAX\left[-u_{i,j,k},0\right] \quad (3)$$

$$k_{eff} = \lambda + \frac{C_p \rho \nu_t}{\sigma_H} \quad (4)$$

Where k_{eff} is effective thermal conductivity, W/mK, it can be calculated by Eq. 4, δx is the central distance between two adjacent grids, m; λ is thermal conductivity for air, W/mK; ν_t is turbulent or eddy viscosity, m^2/s, it depends strongly on the state of turbulence; σ_H is turbulent Prandtl number, dimensionless. k_{eff} and $u_{i,j,k}$ are pre-defined in CFD as a macro. It can be seen from Eq. 3 the heat flux between the virtual walls was described by two parts: heat flux due to the turbulent diffusivity and the thermal diffusivity of air, and heat flux due to air mass flows. If the zonal temperature for the right and left zone is known, then the potential heat transfer between the virtual walls can be calculated.

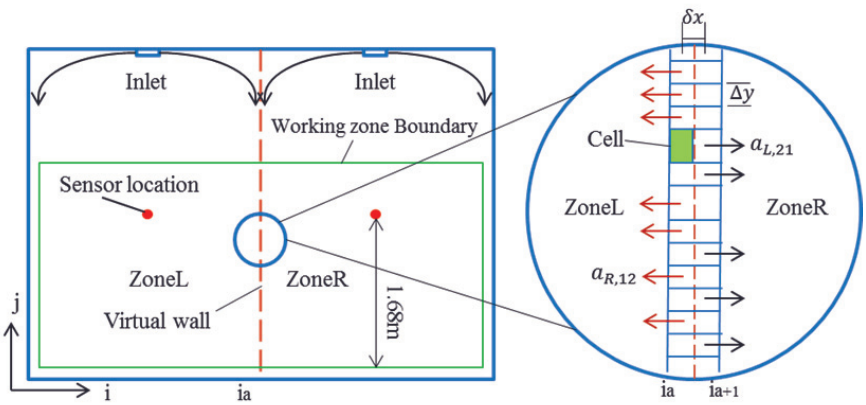

Fig. 1. Calculation heat transfer between virtual walls

2.1 Case study

To calculate the HTC, the 3D model room was established and divided into 2 zones with a virtual wall in the middle as shown in Fig.2, the left zone is served by inlet 1 and inlet 3, while the right region is served by inlet 2 and inlet 4. The detailed boundary condition set-up was shown in Table 1. It is noted that the square ceiling diffuser was described by momentum method. By considering the buoyancy effect near the heater surface, Boussinesq hypothesis was introduced where the density was considered as constant except the buoyancy force in momentum equations. The virtual wall was set to an interior in Fluent which means the heat and mass exchange can occur on this boundary.

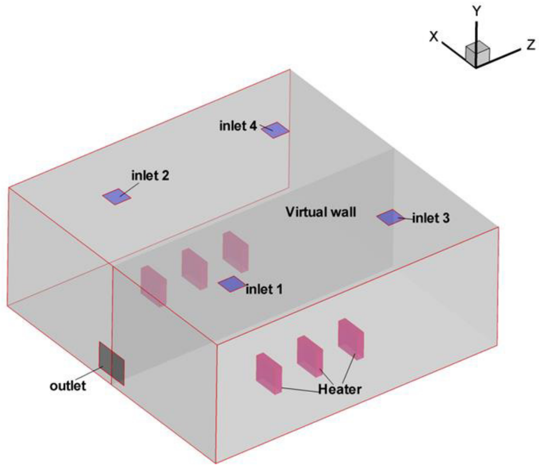

Fig. 2. Configuration of the room

Table 1. Boundary condition setup

Ventilation	Mixing ventilation
Geometry	6.87m×6.72m×2.8m
Supply airflow rate	3000m^3/h
Supply air temperature	17°C
Mesh type and number of grids	Hexahedral-structured, 1.5million
Inlet	4 Square ceiling diffusers, 0.4m×0.4m
Heat source	6 Heaters, 0.6m×0.6m×0.16m, 900W/m^2
Outlet	Outflow, 0.8m×0.6m
Turbulence model	Realizable k-ε model, Standard wall functions
Radiation	Discrete Ordinates (DO)
Numerical schemes	Upwind second-order difference scheme; SIMPLE algorithm
Walls	Ceiling 15W/m^2, North: 30W/m^2, South: 20W/m^2, Floor: 10/m^2, East and West wall: 0
Residuals of convergence	Continuity momentum turbulent kinetic 10^{-4}, Energy 10^{-6}

2.2 Simulation results

Fig. 3 shows velocity and temperature field in x plane with the same supply air flow rate on both sides. The temperature contour was not symmetry, and the thermal plume seems moving to the left side. The reason can be explained by the driven force from the outlet which mounted on the left side wall. Consequently, the temperature on the right side is slightly lower than the left side. Based on the zonal model theory described in the previous section, the energy equation was retrieved, and the heat flux between the virtual walls can be calculated. It is mentioned here the unit of the heat transfer coefficient is

W/K, the potential total heat transfer through the virtual wall can be obtained by multiply the temperature difference between the left and right zone. For accuracy, we use the zonal average temperature to be the represent temperature in each subzone. The HTC was ranged from 0 to 2000 based on the different load distribution as well as the different supply flow rate. The average zonal temperature difference between left and right zone was ranged from 0 to 1°C.

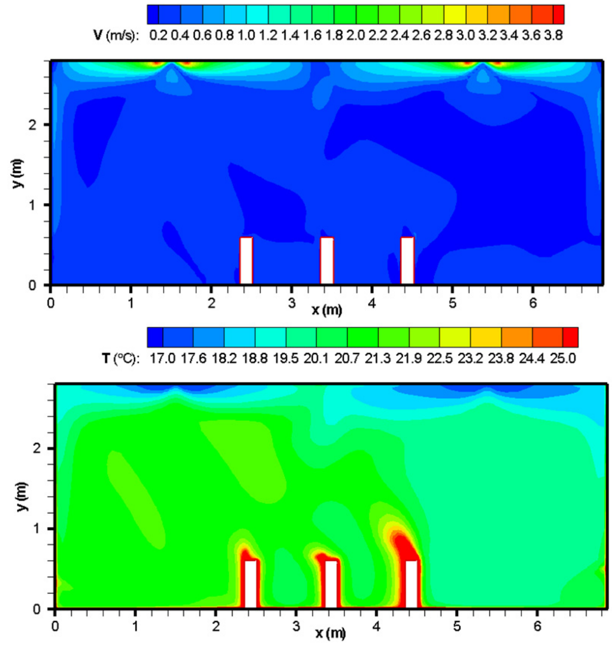

Fig. 3. Contour of velocity and temperature in x cut plane (x=1.5m)

3 Control platform

The heat flux was calculated from the previous section, and the detailed temperature distribution was obtained by CFD. However, the temperature simulated was only in the steady and constant state. The temperature inside under real circumstance varied throughout the day, such as the load changed with occupancy schedule, the absorbed radiation from the outside, which will lead to the cooling load changed with time. Thus, to realize the proposed independent zonal temperature control, a control platform was established in TRNSYS with two separate rooms (Type 56), see Fig. 4, each room was served by an independent supply airflow. The room geometry and boundary conditions were the same with the CFD model. An internal wall divided the room into the left and right room. It was different from the virtual wall in the fluid domain in Fluent because the virtual wall cannot be created in TRNSYS, but there is an interface that the heat flux calculated by fluid dynamics can be fed into the model as internal wall gain. Here a typical case was selected to evaluate the impact of HTC on the indoor temperature control and the controllers. The supply air flow rate for the left and right room was 1780kg/h and 790kg/h with the same load inside (2.7kW for each), the output temperature for the control model was 21.16°C and 22.41°C without adding heat flux into the internal wall. The heat transfer coefficient calculated from CFD was 2000W/K. The left, and the right temperature was 21.2°C and 21.5°C by CFD simulation. Thus the heat flux was 600W and added into the internal wall in control platform; the output temperature was changed to 21.36°C and 21.78°C. If the room temperature set-point was 25°C, Fig. 5 gives the comparison of controller response when the heat exchange between the left and right room was introduced, the overshoot and the settling time didn`t change too much after the heat exchange added into the controller, the temperature set-point can be easily controlled to 25°C within 15 minutes as well. Besides, the introduction of HTC improved the accuracy of the indoor temperatures compared with the CFD simulation results.

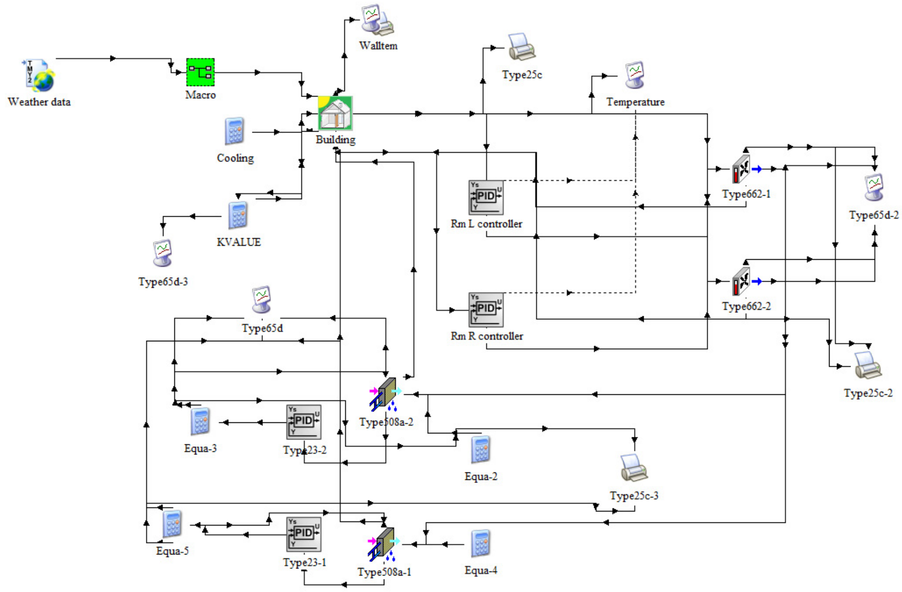

Fig. 4. Zonal temperature control platform

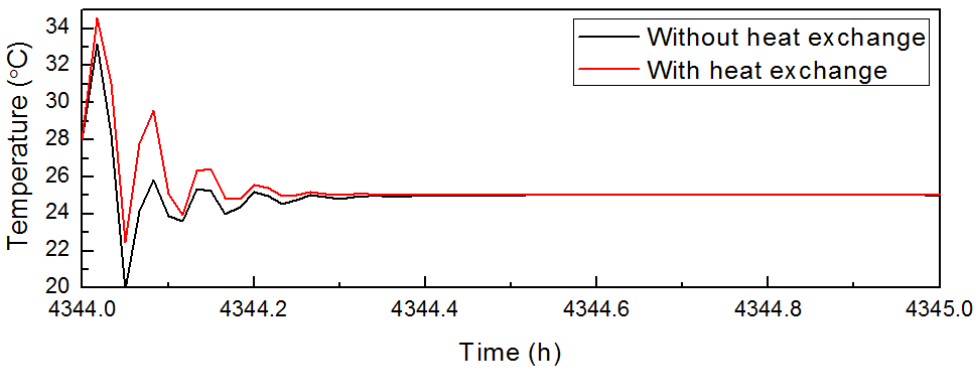

Fig. 5. The response of the controller with and without heat exchange added into the control platform (Left room)

4 Conclusion and discussion

This paper introduced a methodology to calculate the heat transfer coefficient between two adjacent air conditioning zones via a virtual wall aims to improve the independent control for a VAV system. The core idea of an independent zonal temperature control strategy for a large space is dividing the controlling area into a number of subzones and each sub-zone is controlled by an independent VAV box. Firstly, a virtual wall was artificially identified and separated into the fluid domain in Fluent. The heat transfer coefficient (HTC) was derived from the discrete energy equations based on zonal model theory, the mass and heat exchange across the virtual wall was obtained, both the heat transfer due to air mass flows and the heat exchange due to turbulence were considered in the CFD model. A 2-separate VAV control platform was established in TRNSYS, and the HTC was fed to the control platform to evaluate the impact of HTC on the temperature control system. Although the simulation results did not show any significant impact on the performance of the controllers, the temperature on both sides was controlled precisely within the expected range compared with CFD simulation results.

The limitation of this methodology is only a typical case was simulated in CFD and TRNSYS, the dynamic performance of the controllers was not covered here. The coupling between TRNSYS and CFD [9] will be discussed in future work, the dynamic of the heating load inside will be considered, and the heat exchange will be added to the control platform as a constant or variable value to evaluate the performance of the controllers over a period.

Acknowledgements

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References

[1] DOE-EE-0319, Wireless temperature sensors for improved HVAC control, Report of Federal Energy Management Program, U.S. Department of Energy, 2007.

[2] Lin C, Federspiel C, Auslander D. Multi-sensor single actuator control of HVAC systems. International Conference for Enhanced Building Operations2002..

[3] Wang D, Arens E, Webster T, Shi M. How the number and placement of sensors controlling room air distribution systems affect energy use and comfort. 2002.

[4] Kintner-Meyer MC, Brambley MR. Are wireless sensors and controls ready for the building automation industry? Selected case studies and technology development activities. Pacific Northwest National Laboratory (PNNL), Richland, WA (US); 2006.

[5] Zhou P, Huang G, Li Z. Demand-based temperature control of large-scale rooms aided by wireless sensor network: Energy saving potential analysis[J]. Energy and Buildings, 2014, 68: 532-540.

[6] Zhou P, Huang G, Zhang L, et al. Wireless sensor network based monitoring system for a large-scale indoor space: data process and supply air allocation optimization[J]. Energy and Buildings, 2015, 103: 365-374.

[7] Federspiel C. Wireless demand response controls for HVAC systems. 2010.

[8] Peng X. Modeling of indoor thermal conditions for comfort control in buildings[M]. TU Delft, Delft University of Technology, 1996.

[9] Zhai Z, Chen Q, Haves P, et al. On approaches to couple energy simulation and computational fluid dynamics programs[J]. Building and Environment, 2002, 37(8): 857-864.

Biography

Pei Zhou is currently a PhD candidate in City University of Hong Kong, his research focuses on CFD simulation, temperature control.