SIMPLIFIED PREDICTION MODEL FOR VERTICAL PROFILE OF TEMPERATURE AND CONTAMINANT CONCENTRATION IN A ROOM WITH IMPINGING JET VENTILATION SYSTEM

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Abstract

This paper first presents a parametric study using computational fluid dynamics (CFD) as a numerical experiment. A heating element was located at the centre of the room and CO_2 gas was emitted. Two cases of ceiling height, 2,700 and 5,400 mm were studied. Total supply flow rate was also changed as a parameter, and four conditions of 400, 600, 900, 1,200 m^3/h were studied. The number of air supply terminals was changed as well to understand the impact of supply airflow momentum among the cases of the same total supply flow rate, and four cases were studied, i.e., 1, 2, 4, 6 terminals. In total, 32 cases were analysed by CFD. Secondly, the paper presents a simplified prediction model for the vertical profile of temperature and contaminant concentration for IJV system. The model is basically based on "Block Model" where the turbulent diffusivity is the most important parameter. The room blocks are classified into two types, i.e., lower and upper part of a room. The blocks within the same part of the room adopted the same value for turbulent thermal diffusivity, and the appropriate diffusivity was determined. This paper arranges the equation to predict turbulent thermal diffusivity based on specific Archimedes number. By comparing the predicted vertical profiles of temperature and concentration between block model with CFD result, the accuracy of the simplified model is finally verified.
Keywords: impinging jet, temperature stratification, CFD, block model

1 Introduction

The impinging jet ventilation (IJV) system is a relatively new air distribution strategy that supplies air vertically toward the floor (e.g., see Karimipanah and Awbi (2002)). As well as displacement ventilation (DV) system, IJV system can provide higher ventilation effectiveness compared to the conventional mixing ventilation. Due to the medium momentum of supplied air, the IJV system could overcome the difficulties that could exist in DV system with low momentum supply. To date, however, no simplified prediction model to predict indoor environment of an impinging jet ventilated room has been established. Therefore, this study aims to propose a calculation model of the vertical profile of both temperature and contaminant concentration for IJV system. In order to understand the impact of supply air momentum on vertical temperature/concentration profile, a parametric study is performed using CFD where flow rate, number of supply terminal and ceiling height are changed. The simplified prediction method presented in this paper is based on the "Block Model" proposed by Togari et al. (1993). Since the turbulent diffusivity for temperature and concentration is important parameter, this paper presents how to give the appropriate value for these diffusivities, and the accuracy of the block model is verified by comparing the results with CFD.

2 CFD Analysis

A room with IJV system was simulated by using CFD. The basic plan of the room is 9,000 mm long × 5,000 mm wide, which is the same as the full-scale experiment conducted in the previous work by Kobayashi et al. (2017) where CFD was validated by comparison with experiment. This paper first presents the numerical experiment using CFD by changing the number of supply terminal, total flow rate, and ceiling height. Four cases of the number of terminals were studied as shown in ***Figure 1*** to see the effect of supply airflow momentum under the same condition of total supply airflow rate. The total supply airflow rate was also changed as 400, 600, 900, 1,200 CMH, and two cases of the ceiling height were analysed, i.e., CH=2,700 and 5, 400 mm. In total, therefore, 32 cases were simulated by CFD. A heating element of 2.0 kW was located at centre of the room. The steady state calculation was carried out by using SST *k-ω* model with SIMPLE algorithm. The inlet temperature was fixed at 20 °C, and internal radiative heat transfer was also calculated by surface-to-surface model. The CO_2 gas was emitted at the rate of 60 L/h above the heating element.

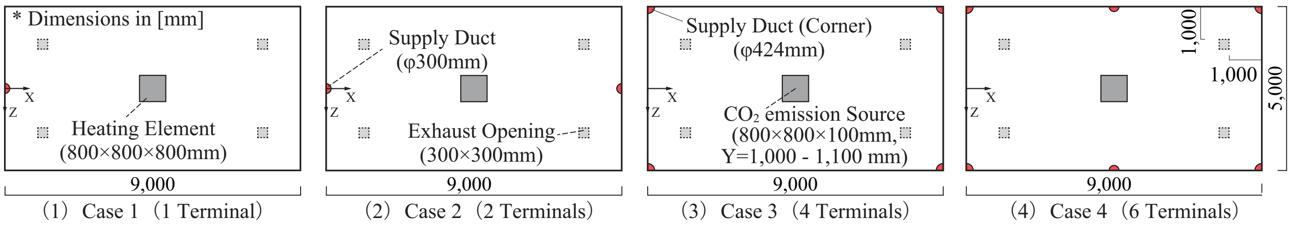

***Figure 1**. Studied room model (Number of IJV supply terminals)*

3 Simplified prediction method using block Model

The simplified prediction model used in this paper is based on the "block model" proposed by Togari et al. (1993). Figure 2 illustrates the schematic of the block mode, where mass conservation and heat transfer by advection and diffusion are solved. A room is classified into three types, i.e., The height of each room block was 270 mm which leads to 10 or 20 room blocks in the case of CH=2,700 and 5,400 mm respectively. ***Figure 3*** gives the details of the heat and mass transfer regarding the room block. ***Table 1*** summarises the basic formula solved. For more details of wall surface current model, see Togari et al (1993).

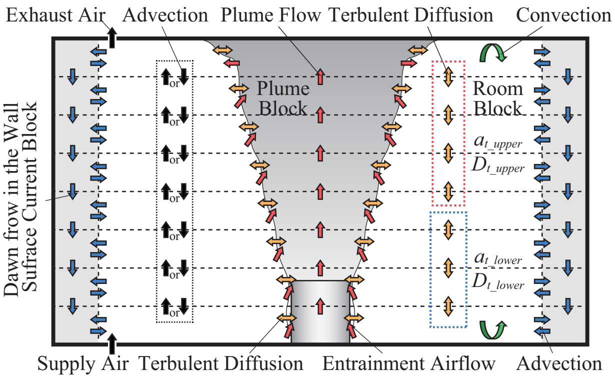

***Figure 2**. Schematic of Block Model*

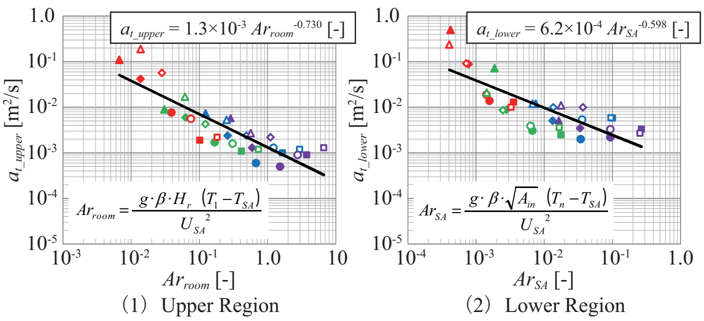

***Figure 4**. Correlation between a_t and Ar*

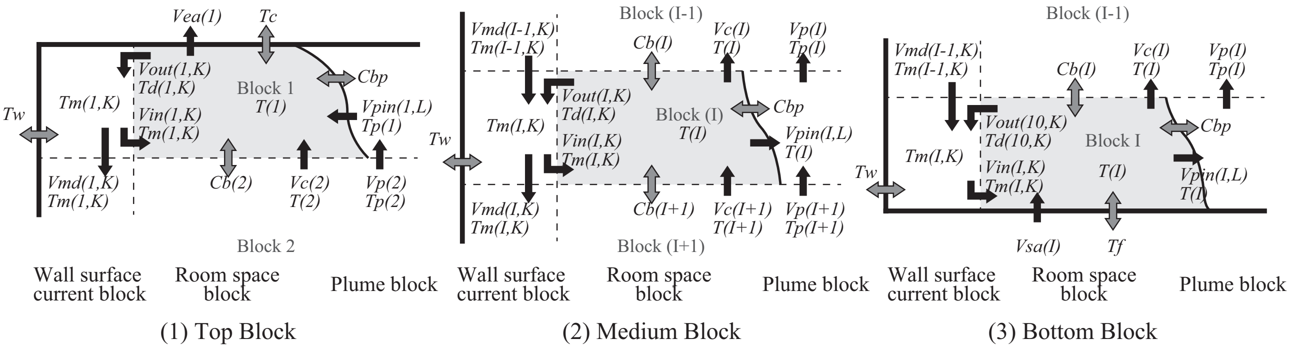

Figure 3: Mass and heat transfer among adjacent control volume

The turbulent diffusivity is the most important parameter which has a significant effect on both temperature and concentration profile. In the proposed prediction method, the horizontal boundary between two room blocks are classified into two types, i.e., lower and upper part of a room. At the boundary within the same part of the room, the turbulent thermal diffusivity is assumed to be uniform, and the appropriate combination of turbulent thermal diffusivity for upper and lower boundary (a_{t_upper}, a_{t_lower} [m^2/s]) were determined based on CFD using the least squares method. Since it is important to predict the diffusivity only from the design factor, a correlation between turbulent thermal diffusivity and specific Archimedes number for upper and lower part (Ar_{room} and Ar_{SA}) were arranged as shown in ***Figure 3*** where regression line is also added as a function of Ar_{room} and Ar_{SA}. As for the contaminant (CO_2) concentration, turbulent mass diffusivity D_{t_lower} and D_{t_upper} was assumed to be the same as turbulent thermal diffusivity at for simplicity. This means the turbulent Schmidt number was assumed to be the same as turbulent Prandtl number.

Table 1. *Equations solved in the block model*

Air flow rate of plume $V_p = 0.005 \times W^{\frac{1}{3}} \times (h - h_0)^{\frac{5}{3}}$	Mass conservation within the room block $\sum_{K=1}^{m} \{V_{in}(I,K) - V_{out}(I,K)\} + V_{sa}(I) - V_{ea}(I) - \sum_{L=1}^{n} V_{pin}(I,L) + V_c(I+1) - V_c(I) = 0$
Mass conservation within the wall-adjacent block $V_{out}(I,K) - V_{in}(I,K) + V_{md}(I-1,K) - V_{md}(I,K) = 0$	Heat balance within the room block (Top block) $\sum_{K=1}^{m} C_p\rho V_{in}(I,K)\{T_m(I,K) - T(I)\} + \sum_{L=1}^{n} C_p\rho V_{pin}(I,L)\{T_p(I,L) - T(I)\} + \underline{C_p\rho V_c(I+1)\{T(I+1) - T(I)\}}$ $+ C_b(I+1)A_b\{T(I+1) - T(I)\} + \alpha_c A_b\{T_c - T(I)\} + \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T_p(I,L) - T(I)\} = 0$
Mass conservation within the plume block $V_p(I+1,L) - V_p(I,L) + V_{pin}(I,L) = 0$ Heat balance within the plume block (Top block) $\sum_{L=1}^{n} C_p\rho V_p(I+1,L)\{T_p(I+1,L) - T_p(I,L)\}$ $+ \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T(I) - T_p(I,L)\} = 0$ Heat balance within the plume block (Medium block) $\sum_{L=1}^{n} C_p\rho V_p(I+1,L)\{T_p(I+1,L) - T_p(I,L)\}$ $+ \sum_{L=1}^{n} C_p\rho V_{pin}(I,L)\{T(I) - T_p(I,L)\}$ $+ \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T(I) - T_p(I,L)\} = 0$ Heat balance within the plume block (Bottom block) $\sum_{L=1}^{n} C_p\rho V_{pin}(I,L)\{T(I) - T_p(I,L)\} + W$ $+ \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T(I) - T_p(I,L)\} = 0$	Heat balance within the room block (Medium block) $\sum_{K=1}^{m} C_p\rho V_{in}(I,K)\{T_m(I,K) - T(I)\} + \underline{C_p\rho V_c(I+1)\{T(I+1) - T(I)\}} - \underline{C_p\rho V_c(I)\{T(I-1) - T(I)\}}$ $+ C_b(I)A_b\{T(I-1) - T(I)\} + C_b(I+1)A_b\{T(I+1) - T(I)\} + \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T_p(I,L) - T(I)\} = 0$ Heat balance within the room block (Bottom block) $\sum_{K=1}^{m} C_p\rho V_{in}(I,K)\{T_m(I,K) - T(I)\} + C_p\rho V_{sa}(I)\{T_{sa}(I) - T(I)\} - \underline{C_p\rho V_c(I)\{T(I-1) - T(I)\}}$ $+ C_b(I)A_b\{T(I-1) - T(I)\} + \alpha_c A_b\{T_f - T(I)\} + \sum_{L=1}^{n} C_{bp}H_bB_p(I,L)\{T_p(I,L) - T(I)\} = 0$ Heat transer coefficient by turbulent diffusion $C_b = a_t \times C_p\rho / H_b$ $\quad C_{bp} = 1.0$ ※The term with underbar is 0 if Vc indicates the outflow from the block.

Nomenclature

V_p : Air flow rate of plume [m^3/s]	V_c : Vertical flow rate between room blocks [m^3/s]	B : Circumferential length of heating element [m]
V_{pin} : Entrainment air flow from block [m^3/s]	T : Room block temperature [℃]	$C_p\rho$: Volumetric specific heat of air [J/(m^3・K)]
V_{in} : Inlet air flow from wall down flow [m^3/s]	T_p : Plume temperature [℃]	A_b : Area of boundary surface of block [m^2]
V_{out} : Outlet air flow to wall down flow [m^3/s]	T_m : Temperature of wall down flow [℃]	H_b : Height of one block [m]
V_m : Mixed wall down flow [m^3/s]	T_{sa} : Supply air temperature [℃]	B_p : Circumferential length of plume [m]
V_{md} : Vertical flow rate of mixed flow [m^3/s]	W : Heat generation rate of heating element [W]	C_b : Heat transfer coefficient between blocks [W/(m^2・K)]
V_{sa} : Supply air flow rate [m^3/s]	h : Height above the floor [m]	C_{bp} : Heat transfer coefficient around plume [W/(m^2・K)]
V_{ea} : Exhaust air flow rate [m^3/s]	h_0 : Distance to virtual point heat source from floor [m]	

Figure 5 shows the extracted results of vertical profile of temperature and CO_2 concentration obtained from the block model and CFD. As for the block model, results of two ways to give turbulent thermal diffusivity are shown, i.e., determined from the least squares method and estimated using equation shown in ***Figure 3***. The results of CFD means the vertical profile of horizontally-averaged value. Based on the validation procedure in the previous work (Kobayashi et al. (2017)), CFD results are regarded reliable results here. In the case of four IJV terminals (Case 3) and low supply flow rate, i.e., low supply momentum, the profile shows stronger stratification. Comparing the results between CFD and block model, relatively good agreement can be seen, which indicates the proposed model considering two parts of the room and correspondingly two diffusivities worked well.

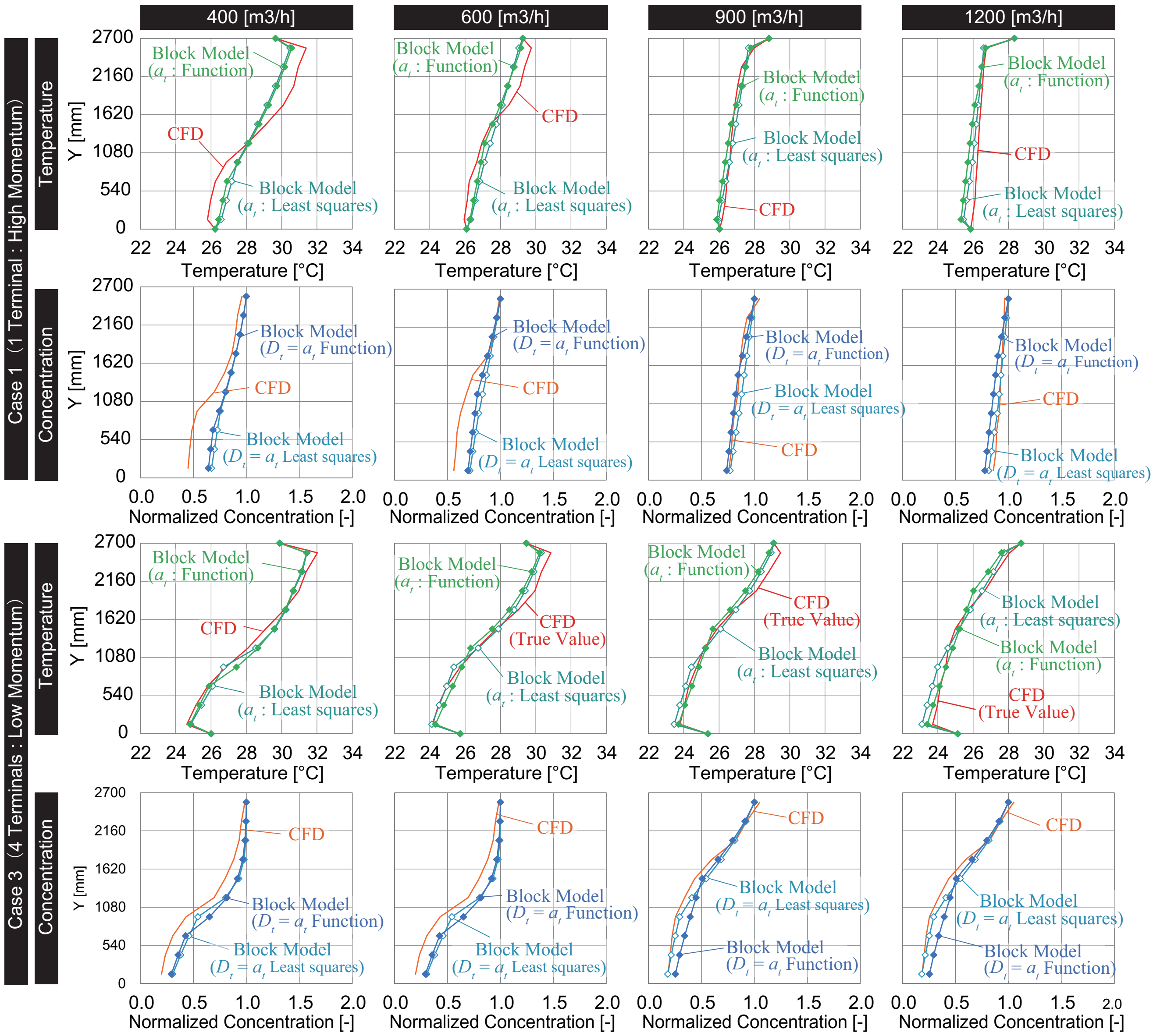

Figure 5. Extracted results of vertical profile obtained from CFD and Block Model (CH=2,700 mm)

5 Conclusions

A simplified model to predict vertical profile of temperature and concentration was proposed based on the block model considering two types of diffusivity, which showed the good performance.

6 References

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