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Effects of airflow rate and supply air temperature on the airflow pattern under active chilled beam system

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***Abstract*—Effects of airflow rate and supply air temperature on the airflow pattern for Active Chilled Beams (ACB) system are investigated in this paper. The air velocity for the air jet near the ceiling are tested and recorded under both isothermal and non-isothermal conditions. The self-similarity for the air jet is observed to be feasible for a certain downstream distance where the vertical maximum velocity is within 1.25 slot heights. A comparison study has been conducted for two mathematical models describing the self-similarity with the experimental data. It turns out that Verhoff's model has an overall better performance than Schwarz and Cosart's model.**

***Keyword*—airflow pattern; active chilled beam; self-similarity; thermal comfort**

I. INTRODUCTION

The Heating Ventilation and Air Conditioning (HVAC) system aims to provide a high respiratory air quality as well as a comfortable living environment. However, thermal comfort has been a major concern because of the complicated air movement and heat transfer. Complaints for the draft and sicknesses which are known as sick building syndromes (SBS) arise intensively as a result of the inferior thermal condition and poor air quality. Chilled beams have been HVAC systems ever since they were introduced in the 1980s. Because of its better performance in terms of energy efficiency, thermal comfort and noise control with less space requirement, ACB system has been increasingly popular in not only Europe, but also North America and Asia. It has been widely utilized in a variety of commercial buildings, schools, laboratories and hospitals [1].

Airflow pattern has a significant effect on the thermal comfort in the occupied zone. It is of great importance to investigate the airflow pattern of ACB system to ensure a satisfied thermal comfort environment. Koskela et al. [2] studied the airflow pattern and thermal comfort in various office environments. They found that the downfall of inlet jets and large-scale circulation causing high air speeds were the two main reasons for the draught risk. The convection airflows had a notable effect on the thermal conditions in the room. Cao [3] suggested that the airflow direction may affect the sensation of a draught, especially when air flowed from behind the neck and towards the face. Fredriksson et al. [4] examined the airflow patterns around the chilled beams based on a thermistor anemometer system. It was demonstrated that the airflow exhibited strong fluctuations which may result in a draught. The airflow pattern was extremely unstable and sensitive to the presence of heat sources.

The research concerning airflow pattern of ACB system has not been sufficiently studied. Some of the research is conducted within a limited testing area or under the condition that the ACB terminal unit is placed on the ground [5-7]. Currently, most of the evaluations on the airflow pattern, for example, heat sources, outer environment and arrangement of ACB terminal unit, are external factors. The influences of internal factors, such as the airflow rate and supply air temperature, are not taken into consideration.

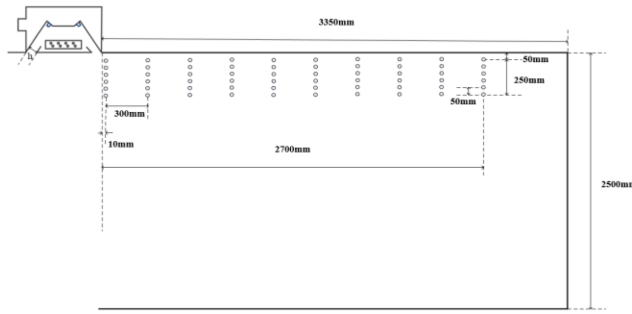
To cover these gaps and achieve a comprehensive understanding of the airflow pattern of ACB system, the velocity profiles of the air jet discharged by ACB system are investigated in this paper. The experiments are conducted under normal working conditions with various supply air temperatures and pressure drops, which is the differential pressure of ACB inlet and atmosphere. Based on the results, a method is developed to judge the valid space for self-similarity of air jet. Two mathematical models are compared on self-similarity. The results provide a guideline for the operation of ACB systems.

II. EXPERIMENTAL SETUP

A. The test room and measurement point distribution

The experiments are conducted in a 7.3m*3.3m*2.5m (L×W×H) thermal isolated room (Fig.1 (a)). As ACB is installed in the middle of the room, the airflow pattern can be considered symmetry on the two sides. Thus, the air velocity is tested on one side covering nearly half of the room. The regions near the wall are ignored because the air velocity is highly influenced by the wall. As the air jet is attached to the ceiling after being ejected for the outlet, testing area is set at the vicinity of the ceiling as a vertical plane in the middle of the outlet with dimension of 2700*300mm (Fig.1 (b)). 60 (6*10) points are measured with a horizontal interval of 300mm and vertical interval 50mm. The jet slot height for this ACB terminal unit is 40mm, which refers to the perpendicular distance for pathway of the supply air as is shown in Fig.3. This definition is referred to Cao et al.[5]'s paper.

(a)



(b)

Fig.1 (a) Thermal isolated room; (b) Measurement point distribution

B. Measurement procedures

The inlet static pressure of 50Pa-250Pa is recommended by the Active and passive beam application design guidebook [8]. Three pressure drops 50Pa, 100Pa and 150Pa, which correspond to three different supply airflow rates, are applied as variables for isothermal cases. As 24°C is the set temperature for this thermal isolated room, it is chosen as the supply air temperature for isothermal cases. According to the guidebook, chilled-water temperature is suggested between 14°C-18°C. To meet this requirement, deductions of 3 °C and 6 °C are imposed to the supply air temperature to investigate the non-isothermal conditions. Totally 5 cases are investigated under isothermal and non-isothermal conditions. Case 1 is the basic case to be contrasted with other cases. The specific measurement condition is demonstrated in Table 1.

Due to wide testing points and the limited experiment condition, the transient air velocity distribution is hardly to be achieved simultaneously. The air velocity is tested one point by one point. However, the testing time delay has little effect on the result because the experiment is conducted under stable initial condition. The stable initial condition is considered to be obtained when the standard deviation for primary air temperature is within 0.1°C and for pressure drop of ACB is within 3Pa for 60 minutes based on EN standards 15116.As the air jet is turbulent air, the air velocity fluctuates continually within a certain range. As a result, the velocity is measured with a sample time of 120 seconds. The sample rate is set as 1 Hz.

TABLE 1 MEASUREMENT CONDITIONS

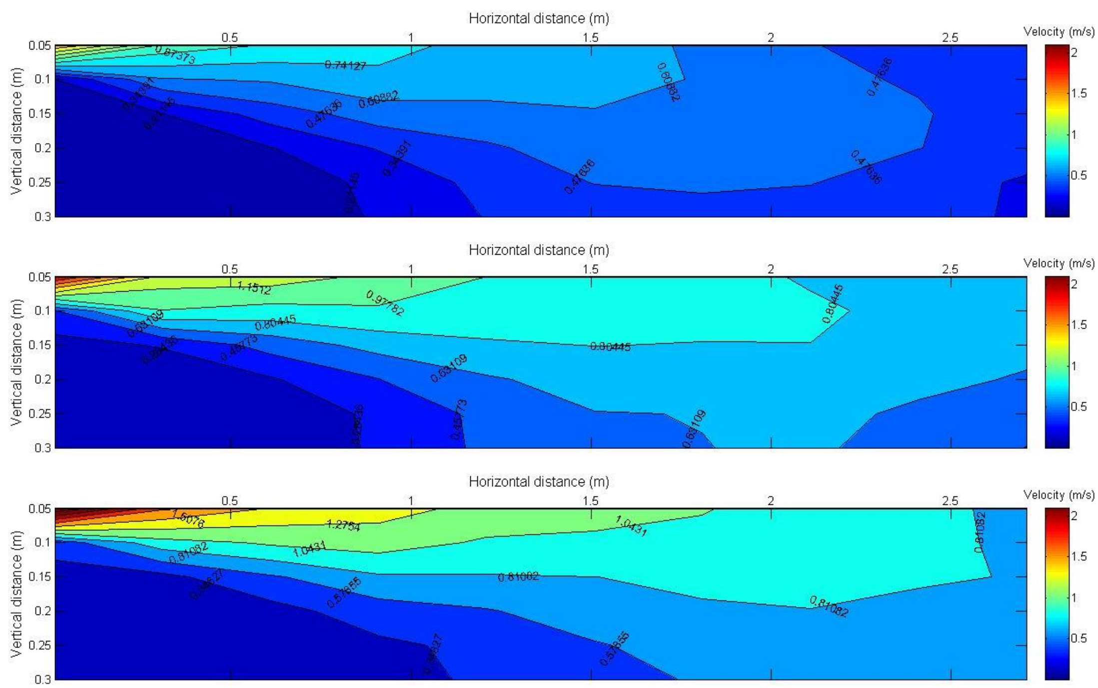
Case	Pressure drop	Supply air temperature	Room temperature	Differential temperature between supply air and room air
1	50Pa	24°C	24°C	0°C
2	100Pa	24°C	24°C	0°C
3	150Pa	24°C	24°C	0°C
4	50Pa	21°C	23°C	2°C
5	50Pa	18°C	22.7°C	4.7°C

III. RESULTS

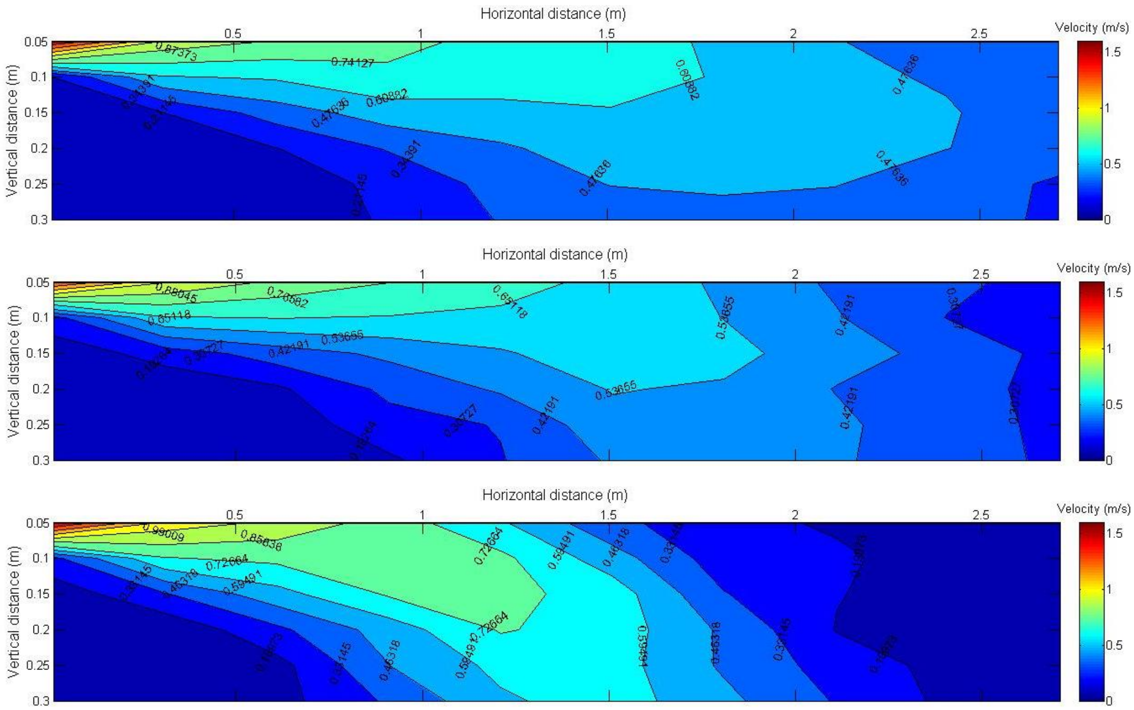
Totally 60 points are measured in the testing area. 120 velocity data are collected for each point. The average velocity is calculated as the velocity of the related point in order to reduce the error. Based on the data, the velocity contour are plotted and analyzed in the following part.

A. *Velocity contours*

The velocity contours depicted in Fig.2 for all cases are plotted by Matlab. The horizontal axis stands for the horizontal distance from the ACB outlet, while the vertical axis represents the vertical distance from the ceiling. Case 1 is plotted repetitively with different velocity scale for the purpose of comparison. For isothermal cases (Fig.2 (a)), it can be seen that the air jet expands as soon as it is discharged from the outlet of the slot as a consequence of the entrainment of the surrounding air. The spreading angle shown from the velocity contour is the smaller when the pressure drop is higher. In addition, the air jet stays attached to the ceiling over a long downstream distance for all three cases. The velocity decay is also clearly shown through contours. With respect to the non-isothermal cases (Fig.2(b)), an obvious air jet bending in the middle of the half-room can be observed when supply air temperature is at 18°C and the corresponding temperature difference between supply air and room air is 4.7°C. This phenomenon reflects that the air jet starts to detach from the ceiling after a distance around 1.2m for case 5. By comparing from these three cases, the bigger the temperature difference between supply air and room air, the more apparent this detachment is.



(a)



(b)

Fig.2. (a) Velocity contours for isothermal conditions (case 1, 2, 3); (b) Velocity contours for non-isothermal conditions (case 1, 4, 5)

B. *SELF-SIMILARITY OF THE AIR JET*

As the turbulent air jet has characteristic of self-similarity, which refers to the vertical velocities at different horizontal distances have similar profiles, as is presented in Fig.3. It can be elaborated as the ratio of local velocity (u) divided by the maximum velocity (U_m) has certain relationship with the local vertical position (y) divided by the vertical position when the velocity is equal to half of the maximum velocity ($y_{1/2}$).

The self-similarity can be described by numerical models. Verhoff [9] proposed an empirical model

$$u / U_m = 1,48\eta^{1/7}[1-\mathrm{erf}(0.68\eta)] \quad (3)$$

where $\eta = y / y_{1/2}$ and $y_{1/2} = 0.068(x+10h)$. h is the slot height, which is 0.04m for this ACB terminal unit. x is the horizontal distance from the outlet of ACB.

Schwarz and Cosart's model [10] is expressed as

$$u / U_m = \exp[-0.937(\eta-0.14)^2] \quad (4)$$

These two models are particularly used to describe the plane wall jet, which fit the characteristics of air jet discharged from ACB, in terms of the normalized velocity and normalized distance to the ceiling. However, this self-similarity is only valid under certain downstream distance after developed and before impinging on the wall. If the air jet is detached from the ceiling, the self-similarity is not suitable anymore. A good similarity was revealed by Cao et al. [7] in the region at a distance of 600mm-2000mm in the case of Re=2667 and the data deviated from the theoretical profiles after 2000mm. They also found that the jet similarity may be affected by both the initial Reynolds number of the jet and the intensity of the turbulence [5].

In order to test the self-similarity, the value of u, y and Um can be achieved from the experiment. $y_{1/2}$ is calculated through interpolation method of "Piecewise Cubic Hermite Interpolating Polynomial" (PCHIP) based on Matlab [11]. The relationship of y and normalized velocity (u/Um) is plotted in Fig.4 (a) for isothermal cases and Fig.4 (b) for non-isothermal cases. It can be found out that some curves are distorted at right bank and $y_{1/2}$ is unable to be obtained. These twisted curves are the ones that vertical maximum velocity goes beyond y=0.05m, which is 1.25 slot heights. It can be inferred that when the vertical maximum velocity is beyond around 1.25 slot height, the self-similarity is not suitable for the air jet. This result may explain why the data after 2000mm does not fit the theoretical profile in Cao et al.'s report [7].

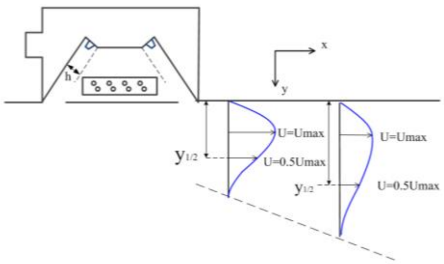
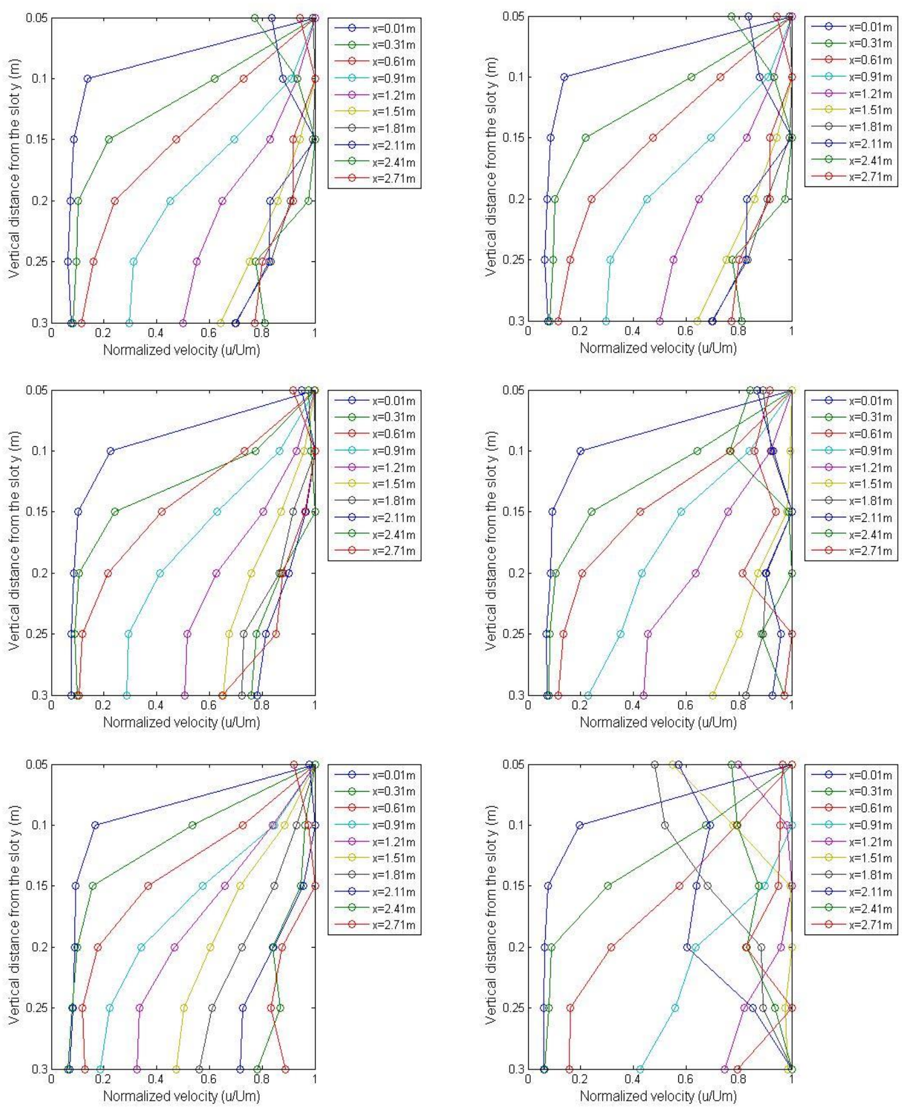


Fig.3 Self-similarity

Based on the conclusion above, the two models are also compared with the experimental data whose vertical maximum velocity is at 1.25 slot height (y=0.05m) for case 3 in Fig.5. It can be seen that the data fit the two models well. Mean absolute errors are calculated for the two models in Fig.6. Mean absolute errors are calculated according to the following formula,

$$\mathrm{MAE}=\frac{1}{N}\sum_{i=1}^{N}\left|e_i\right| \quad (5)$$

where MAE is the mean absolute error, N is the vertical testing points, which is 6 in this paper, e_i is the error between the experiment result and calculated result. It can be drawn from Fig.9 that Schwarz and Cosart's model describes the velocity profile better at the location close to the outlet of ACB. However, Verhoff's model has a better performance when the air jet is a little bit far away from the outlet. Overall, Verhoff's model describes the self-similarity more precisely.



(a) (b)

Fig.4 (a) Relationship of y and normalized velocity (u/Um) for isothermal conditions (case 1, 2, 3); (b) Relationship of y and normalized velocity (u/Um) for non-isothermal conditions (case 1, 4, 5); where x is the horizontal distance from the outlet of ACB

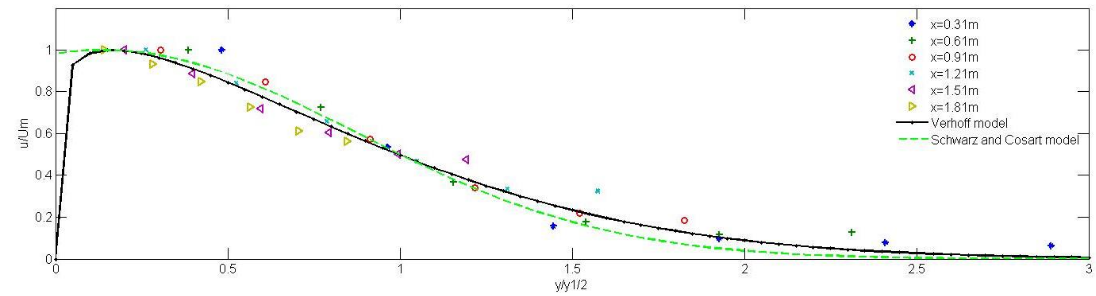


Fig.5 Model comparison

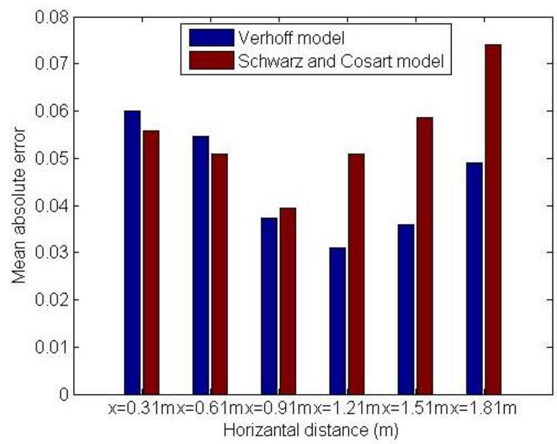


Fig.6 Mean absolute errors of two models

IV. CONCLUSION

The air flow patterns of the air jet discharged by ACB system under various airflow rate and supply air temperature were fully investigated in this paper. The higher pressure drop contributed to a better air attachment, while the bigger differential temperature between the supply air and the room air hindered this effect. Therefore, in order to guarantee a good thermal comfort performance, the pressure drop and the differential temperature should be carefully considered. The pressure drop of 50Pa-150pa was suggested for ACB system and the differential temperature between the supply air and the room air above 4.7°C was not recommended. Furthermore, the self-similarity models were unable to describe the air jet when the air jet was detached from the ceiling as the velocity profile was skewed. The mathematical model proposed by Verhoff and Schwarz & Cosart were compared with the experimental data. Overall, Verhoff's model was better than Schwarz and Cosart's as this model fit most of the experimental data.

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