INVESTIGATION ON THE RELATIONSHIP BETWEEN FLOW PATTERN AND AIR AGE

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ABSTRACT

Eight mechanically ventilated flow patterns have been conducted in a test chamber. The air age in test chamber is measured with tracer gas technique. A CFD program named as STACH-3 is developed with the transport equation of air age in it. The predicted air age with STACH-3 is compared with the experimental results. It is shown that the computed air age agrees well with the experimental results except a few points. The relationship between flow pattern and air age distribution for the test chamber is analyzed with not only the predicted but also the experimental results.

Keywords: CFD, Tracer gas, Air age, Ventilation

1 INTRODUCTION

It is reported that most persons spend 80~90% of their time indoors[1]. Therefore, indoor environment is very important and people have paid more attention to it in the past decade. To evaluate indoor environment, one of the essential factor is indoor air quality (IAQ). Indoor air quality can influence not only comfort but also people's health. The deterioration of indoor air quality results in a variety of health and comfort complaints. Most of the symptoms are associated with sick building syndrome (SBS). Many researchers have investigated causes contributing to SBS, including ventilation, indoor VOC source, cross-contamination, microbial contamination and so on[1,2,3]. According to these investigations, poor ventilation is the most important factor that causes SBS.

A lot of parameters or index have been proposed to evaluate IAQ, such as macro air exchange rate[4], air change efficiency, ventilation efficiency, local air change efficiency, local ventilation index, purging air flow rate[5]. Many of theses parameters are associated with air age, which is generally defined as the time that has elapsed since air element entered the room[5]. There are a lot of factors influencing air age, such as types of diffusers, locations of supply outlets and return inlets, configuration of buildings, air flowrate etc. In fact, once the flow pattern is not changed, the distribution of air age will not be different.

The aim of this paper is to get the distribution of air age at different kinds of air diffusion in a test chamber and to investigate the relationship between flow pattern and air age.

2 METHODOLOGY

There are two main ways to get parameters of air motion. One is from full-scale test, the other is from numerical analysis. Some articles have been published on the experimental investigation of air motion[6], but such investigations are very expensive and detailed measured data are not available. Meanwhile, it is impossible to conduct adequate experiments that can deal with all eventualities. With the development of computer and the advancements of CFD (Computational Fluid Dynamics), a new approach which can predict air motion with CFD modeling was presented, as reviewed by Nielsen[7]. Although a lot of papers have been published on indoor air quality and thermal comfort in the last few years[8,9,10], there are few papers on the relationship between air flow pattern and air age.

- 2.1 Mathematical Modeling of Air Flow and Diffusion

The motion of air flow can be described by the laws of conservation of mass, momentum (u, v, w) and energy (h) as well as the transport laws of mass diffusion and heat transfer. The transport equations of turbulence energy (k) and its dissipation rate (ε) are also involved in the computations. Since buoyancy takes an important role in air flow, it is also considered in the equations. All the governing equations can be expressed in a general form:

$$div(\rho \vec{u} \varphi - \Gamma_\varphi grad\varphi) = S_\varphi \quad (1)$$

where φ stands for a general fluid property such as u, v, w, h etc. and $\rho, \vec{u}, \Gamma_\varphi, S_\varphi$ are density, velocity vector, effective diffusivity coefficient and source rate per unit volume, respectively. When φ=1, the equation changes into the continuity equation.

- 2.2 Air Age Test with Tracer Gas Technique

There are three kinds of injection of tracer gas: pulse method, step-up method and step-down method.

(1) The pulse method: a small amount of tracer gas is introduced to the supply duct;

(2) The step-up method: a continuous and constant flow of tracer gas is introduced to the supply air duct;

(3) The step-down method: as the concentrations have reached their equilibrium values in a step-up procedure, the addition of tracer gas is stopped at τ=0.

According to the previous research, the air age at an arbitrary point with tracer gas technique is as following[5]:

The pulse method:

$$\tau_p = \frac{\int_0^{\infty} \tau C_p(\tau) d\tau}{\int_0^{\infty} C_p(\tau) d\tau} \qquad (2)$$

The step-up method:

$$\tau_p = \int_0^{\infty} [1 - \frac{C_p(\tau)}{C_p(\infty)}] d\tau \qquad (3)$$

The step-down method:

$$\tau_p = \frac{\int_0^{\infty} C_p(\tau) d\tau}{C_p(0)} \qquad (4)$$

Where τ_p is the air age at an arbitrary point, $C_p(\tau)$ is the concentration of tracer gas at the point when time is τ.

- 2.3 Transport Equation of Air Age

The diffusion of tracer gas obey the species equation, which (turbulent or laminar flow) is as following:

$$\frac{\partial C_p}{\partial \tau} + \frac{\partial}{\partial x_j}(u_j C_p) = \frac{\partial}{\partial x_j}(\Gamma \frac{\partial C_p}{\partial x_j}) + S_C \qquad (5)$$

where C_p is the concentration of tracer gas, u is velocity, Γ is the diffusive coefficient, S_C is the source term (the generation per unit volume). Subscript j can be 1, 2 or 3, which indicates the three space coordinates x, y or z. If the subscript j is repeated in a term, it means the summary of three space coordinates.

After integration and substitution, Li *et al* got the transport equation of air age as following[11]:

$$\frac{\partial}{\partial x_j}(u_j \tau_p) = \frac{\partial}{\partial x_j}(\Gamma \frac{\partial \tau_p}{\partial x_j}) + 1 \qquad (6)$$

Although air age is defined as the time that has elapsed since air element entered the room, it has some transport properties. The transport equation of air age can also be expressed in the standard form, i.e. equation (1).

- 2.4 STACH-3

The equations describing air flow and air age were translated into a computer program, i.e., STACH-3. The computer code was developed at Tsinghua University by Li[12]. The program was applied for ventilation and distribution of air age and fairly good results were predicted[11,13].

In this paper, eight mechanically ventilated flow patterns were conducted in a test chamber. The air age of five points in the test chamber was measured with tracer gas technique. Both the flow pattern and the distribution of air age were calculated with STACH-3.

3 EXPERIMENT AND SIMULATION

The research was conducted in a test chamber as shown in Figure 1. The chamber is 5m long, 3.5m wide and 3m high. There are two air supply outlets (A and B) and five air return inlets (from 1 to 5). The air supply outlets are round, diameter of A is 150mm and B 210mm. Air supply outlet A is at the ceiling and B at sidewall. The dimensions of air return inlets 1 to 5 are 350×350, 350×350, 250×350, 500×350 and 350×350 (units: mm) respectively.

Eight mechanically ventilated cases labeled as A1, A4, A5, B1, B2, B3, B4 and B5 were conducted in the test chamber. The first character of case label indicates the air supply outlet and the second indicates the air return inlet. For example, Case A1 means the air supply outlet is A and the return inlet is 1. There are five points to be measured in every case, which are labeled as (1) to (5).

For every case, the air age of the five points was measured with step-down method and both the flow pattern and the distribution of air age were calculated with STACH-3.

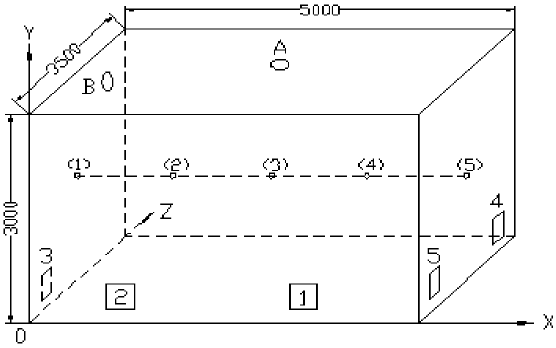


Figure 1 Schematic of the test chamber

The measured and predicted air age for the eight cases are listed in Table 1. It shows that the measured and predicted air age agrees well qualitatively and agrees quantitatively except a few points. The discrepancy comes from two aspects, one is from test, the other from numerical model. It is well-known that the mechanically ventilated air flow is turbulent and turbulence takes an important role in the diffusion of tracer gas, which results in difference between two measurements even under same operating conditions. As far as numerical model is concerned, the simplification of physical model and turbulence model will also result in discrepancy. Nevertheless, the measured and predicted results sound reasonable.

4 RESULTS AND DISCUSSION

- 4.1 Validation of STACH-3

Table 1 Comparisons between measured and predicted air age (unit: second)

Case	Point	Measured	Predicted	Case	Point	Measured	Predicted
A1	(1)	215	221	B2	(1)	269	243
	(2)	224	286		(2)	294	225
	(3)	197	229		(3)	308	286
	(4)	225	330		(4)	303	247
	(5)	207	257		(5)	234	195
A4	(1)	257	188	B3	(1)	245	198
	(2)	285	223		(2)	270	185
	(3)	271	186		(3)	293	218
	(4)	288	236		(4)	282	170
	(5)	258	160		(5)	207	142
A5	(1)	237	219	B4	(1)	259	334
	(2)	257	212		(2)	286	416
	(3)	243	173		(3)	305	289
	(4)	270	242		(4)	297	284
	(5)	242	166		(5)	217	246
B1	(1)	275	225	B5	(1)	250	299
	(2)	304	246		(2)	276	262
	(3)	317	226		(3)	298	289
	(4)	312	223		(4)	287	238
	(5)	236	184		(5)	212	225

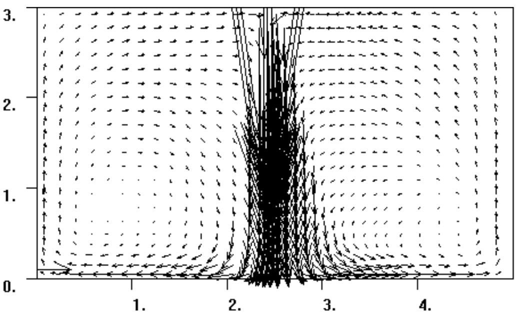
- 4.2 Flow Pattern and Distribution of Air Age

The predicted average air age for 8 cases is shown in Table 2.

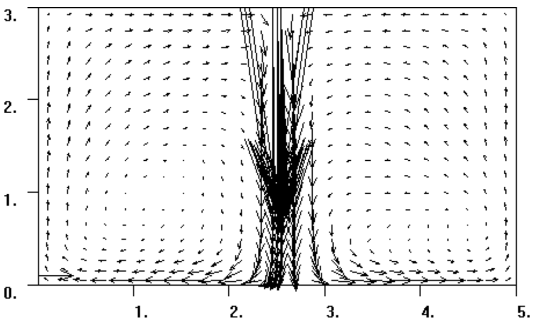
Table 2 The predicted average air age for 8 cases

Case	Average air age (s)	Case	Average air age (s)
A1	211	B2	278
A4	263	B3	256
A5	244	B4	269
B1	286	B5	262

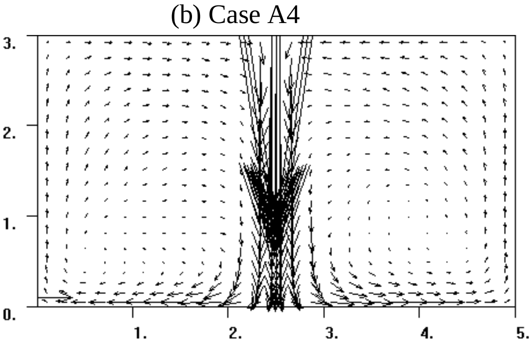
The flow patterns of the eight cases are shown in Figure 2 and distributions of air age in Figure 3.



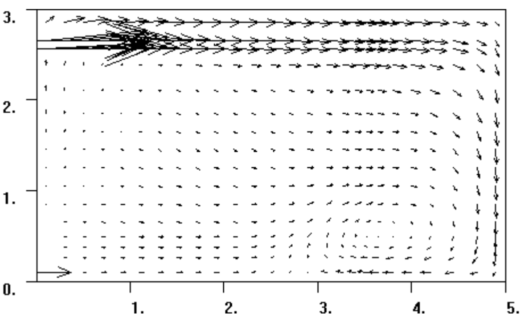
(a) Case A1



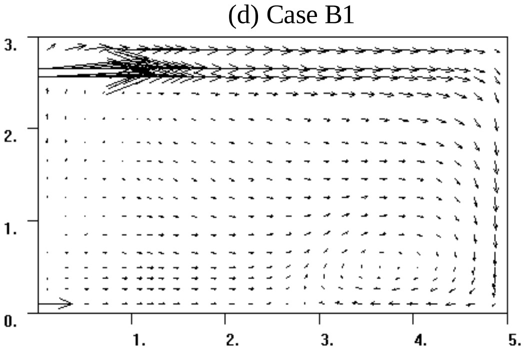
(b) Case A4



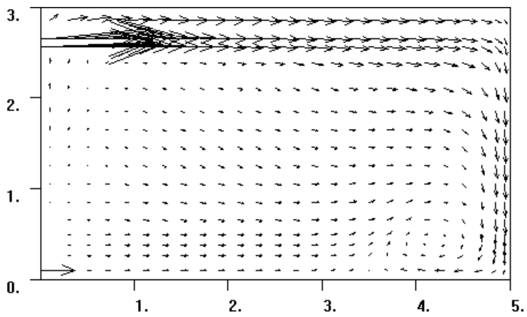
(c) Case A5



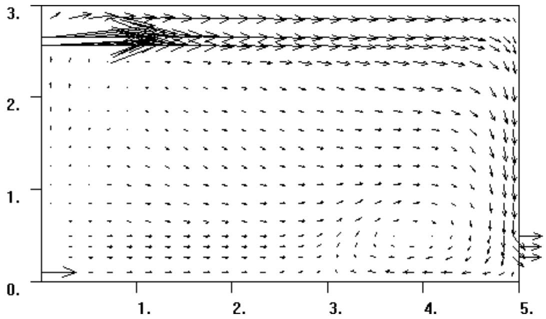
(d) Case B1



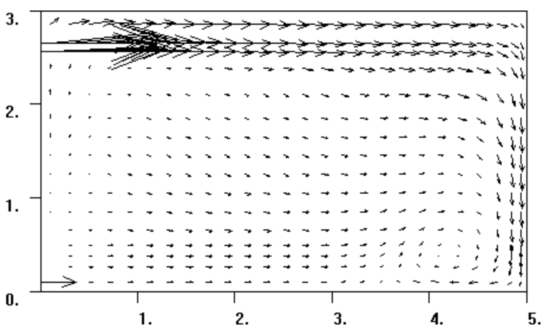
(e) Case B2



(f) Case B3

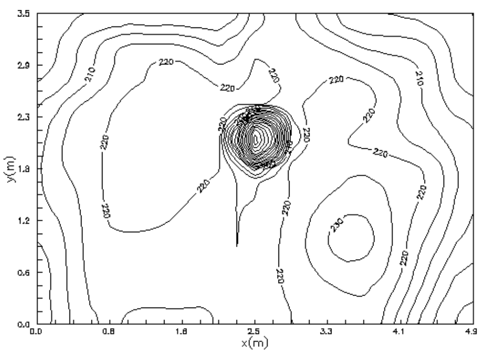


(g) Case B4

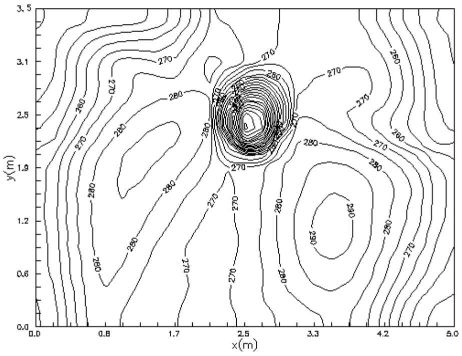


(h) Case B5

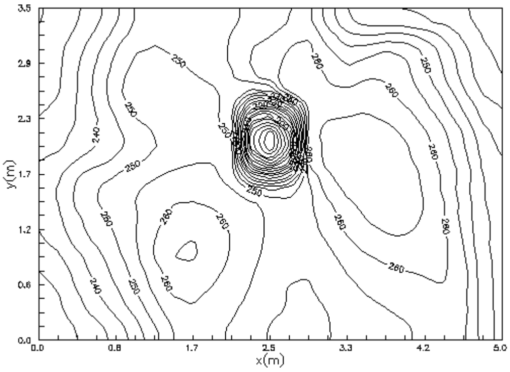
Figure 2 Flow pattern in vertical section across the supply outlets
Note: the arrow in the left bottom is 1m/s



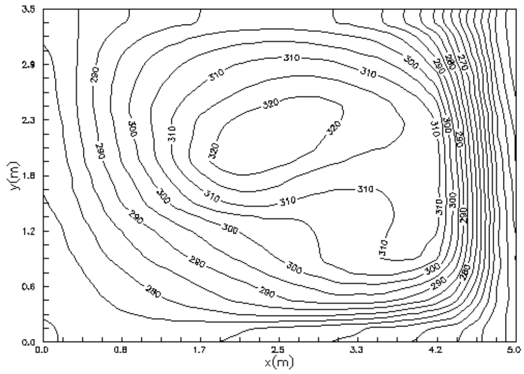
(a) Case A1



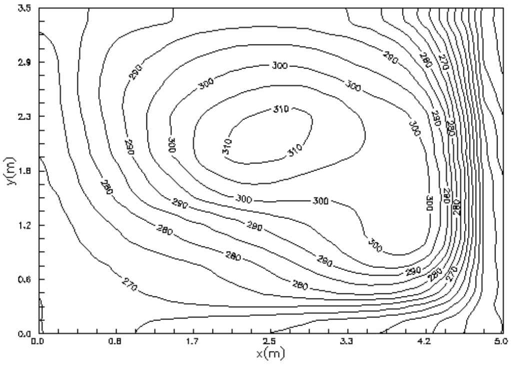
(b) Case A4



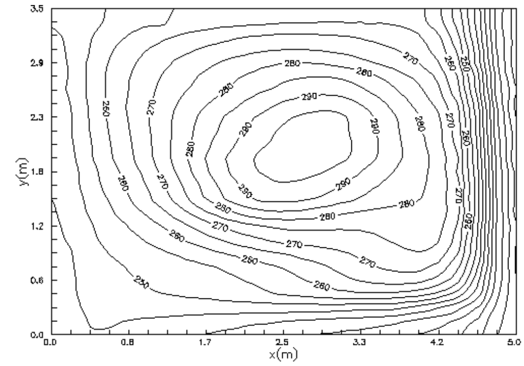
(c) Case A5



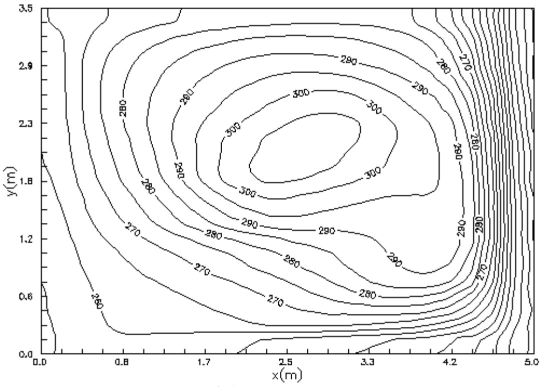
(d) Case B1



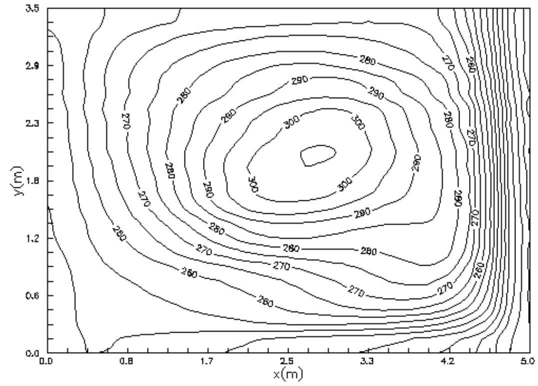
(e) Case B2



(f) Case B3



(g) Case B4



(h) Case B5

Figure 3 Distribution of air age in horizontal section at 1.5m above floor

- 4.3 Discussion

The locations of supply air outlets and return air inlets are the most important factor to influence flow pattern. Generally speaking, the location of supply air outlets is much more important to the flow pattern than that of return air inlets. It can also be shown in Figure 2 and Figure 3. There are two kinds of supply air outlets, one is from ceiling and the other from sidewall. Although there are five kinds of return air inlets, the flow pattern can be divided into two kinds according to the location of supply air outlets. Cases A1, A4 and A5 have almost the same flow pattern as shown in Figure 2(a), 2(b) and 2(c), which can be simplified as supply from ceiling. Cases B1, B2, B3, B4 and B5 have almost the same flow pattern as shown in Figure 2(d), 2(e), 2(f), 2(g) and 2(h), which can be simplified as supply from sidewall.

Different flow pattern results in different air age distribution. That is why the distributions of Cases A1, A4 and A5 are very different from that of Cases B1, B2, B3, B4 and B5 (see Figure 3). However, Cases A1, A4 and A5 have similar distributions of air age and Cases B1, B2, B3, B4 and B5 have similar distributions as well.

Figure 2(a), 2(b) and 2(c) show that the supply air flows vertically to the floor and then to the sidewalls. There are recirculations between sidewalls and supply air outlet, which results in a much younger air down the supply air outlet, older air near sidewalls and oldest air between sidewalls and supply air outlet, as shown in Figure 3(a), 3(b) and 3(c).

There are some differences between supply from sidewall and supply from ceiling. Suppled from sidewall, the air flows forward to the opposite wall, then comes down to the floor and flows along the floor to the sidewall, as shown in Figure 2(d), 2(e), 2(f), 2(g) and 2(h). This kind of flow pattern results in younger air near the opposite wall, older air near the sidewall below the air supply outlet and oldest air between the sidewall and face wall, as shown in Figure 3(d), 3(e), 3(f), 3(g) and 3(h).

It is certain that the location of return air inlet influences the distribution of air age as well. However, the influence is not great, which can be seen in Table 2, Figure 2 and Figure 3.

5 CONCLUSIONS

Throughout the past decade, more and more attentions have been paid to the indoor environment. Among the factors influencing indoor environment, poor ventilation has become the most important one to cause SBS. That is why investigators pay more attentions to air flow and air age.

The air flow pattern and distribution of air age in a test chamber are investigated numerically. The test chamber is equipped with two supply air outlets and five return air inlets. The air age of five points in the test chamber is measured by tracer gas technique and then compared with the predicted results.

Some conclusions can be drawn from the analysis above:

(1) CFD modeling is a new and effective approach to evaluate flow pattern and distribution of air age. It is a much cheaper and less time-consuming method than tracer gas technique and detailed distribution of air age is available. The predicted air age agrees with experimental ones qualitatively and quantitatively.

(2) Although the location of return air inlet influences the flow pattern and the distribution of air age, the influence is not great. The location of supply air outlets is much more important to the flow pattern and distribution of air age than that of return air inlets.

(3) For the cases of air supply from ceiling, the air age is much younger down the supply air outlet, older near sidewalls and oldest between sidewalls and supply air outlet. For the cases of air supply from sidewall, the air age is much younger near the face wall, older near the sidewall below the air supply outlet and oldest between the sidewall and face wall.

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