An algorithm for calculating fresh air age in central ventilation system

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Abstract Fresh air age is an important index to evaluate indoor environment. The conventional method for measuring or calculating fresh air age is only suitable for simple ventilation systems and not for central ventilation systems. In this paper, an algorithm for calculating fresh air age in central ventilation system is presented, which is based on the analysis of air flow in duct and air mixing. An example is given to illustrate the algorithm. The fresh air age in every ventilated room and duct can be acquired after all rooms and duct are directly calculated in turn without iteration. The algorithm is suitable for different central ventilation systems.

Keywords: ventilation, indoor air quality (IAQ), fresh air age, algorithm.

Since most people spend 80%—90% of their time indoor[1], indoor environment is very important to human health. For a long time, indoor environment is mainly described by temperature and humidity. The main target of air-conditioning system is to provide proper indoor temperature and humidity. With the wide adoption of air-conditioning system in the buildings and the application of a large amount of the so-called “energy-saving building”, some new understanding of the evaluation of indoor environment is available.

From the 1970s, since energy-saving gradually became an important aspect in the design of air-conditioning system, the amount of fresh air was decreased. On the other hand, large amount of volatile organic compound (VOC) was volatilized in buildings because of the wide use of organic compounds in indoor decoration, which deteriorated indoor environment[2]. People living in the so-called “energy-saving” buildings often suffer from such symptoms as red-eyes, snivel, sour throat, fatigue, headache, nausea, itch and so on[3]. According to the definition of World Health Organization (WHO), a building that causes such syndromes is called “sick building”. A survey that involves more than 50000 offices in America indicated that only 20% offices were of health quality, 40% of acceptable quality and 40% were sick buildings. Among the sick buildings, 10% were seriously sick buildings which had poor indoor environment[4]. The question of indoor air quality (IAQ) is thus raised.

According to the ASHRAE STANDARD62-89[5], acceptable IAQ should ensure that the contamination level is smaller than the index set by authoritative institutions and that most people (more than 80%) in the environment do not complain. IAQ is determined by two aspects: performance of ventilation system and characteristics of indoor contamination. An evaluation from

National Institute for Occupational Safety and Health (NIOSH) indicates that a large part of sick buildings are caused by poor-designed ventilation systems[6].

Indoor airflow pattern, which is an important part of ventilation system, has a great influence on IAQ. The poor-designed airflow pattern caused 45%—65% of bad IAQ problems[2]. In order to assess the ventilation efficiency, a lot of parameters and indexes have been proposed, such as macro air exchange rate[7], air change efficiency, local air change efficiency, local ventilation index and purging airflow rate[2]. A majority of these parameters are associated with fresh air age. According to Sandberg, fresh air age is generally defined as the time since fresh air element entered the room[8]. The smaller the fresh air age, the better the IAQ. Consequently, fresh air age has become an important index of evaluating indoor environment besides temperature and humidity.

Air age is conventionally measured with tracer gas technique[9—11], which is expensive, time-consuming and troublesome. In recent years, numerical method has been adopted [12—17]. But till now, both methods are only fit for the simple ventilation system in which only one room is ventilated. As more and more central ventilation systems, in which a number of rooms are ventilated with one air handling unit, are put into use, it is of significance to develop a fast method to determine fresh air age in such systems.

1 Traditional method for measuring and calculating fresh air age

Because air group at an arbitrary point involves molecules with different fresh air age, each population of air molecules may be characterized by their statistical cumulative air age distribution $F(\tau)$ and corresponding frequency distribution $f(\tau)$. $f(\tau)$ represents the ratio of molecules with an age of τ in air group, and $F(\tau)$ represents the ratio of molecules with an age less than τ in air group. The general relationship between $F(\tau)$ and $f(\tau)$ is as follows:

$$\int_0^{\tau} f(\tau)\mathrm{d}\tau = F(\tau). \tag{1}$$

Because air age τ_p is the average age of the air group, while $f(\tau)$ is known, it can be calculated by

$$\tau_{\mathrm{p}} = \int_0^{\infty} \tau\ f(\tau)\mathrm{d}\tau. \tag{2}$$

Tracer gas method can be used to acquire air age through measuring tracer gas concentration versus time. “Step-up method” and “step-down” method are the commonly used tracer gas methods. In step-up method, a continuous and constant flow of tracer gas is injected into the air duct; in step-down method, the addition of tracer gas is stopped as the concentration reaches equilibrium in a step-up procedure. After the concentration is recorded, the air age can be calculated by

(i) the step-up method:

$$\tau_{\mathrm{p}} \int_0^{\infty} = \left[1 - \frac{C_p(\tau)}{C_p(\infty)}\right]\mathrm{d}\tau, \tag{3}$$

(ii) the step-down method:

$$\tau_{\mathrm{p}} = \frac{\int_0^{\infty} C_p(\tau)\mathrm{d}\tau}{C_p(0)}, \tag{4}$$

where $C_{\mathrm{p}}(\tau)$ is the concentration of tracer gas at time τ. Either step-up method or step-down method needs to measure the tracer gas concentration versus time. In a system with complex duct configuration or multiple rooms, the concentration equilibrium can hardly be achieved, so the fresh air age can hardly be measured by step-down method or step-up method. That is why tracer gas method can only be used in simple ventilation system.

To overcome the disadvantages of tracer gas method, such as time-consuming, expensiveness and disturbance to living and work, based on tracer gas method, Li et al.[13] got the transport equation of air age

$$\frac{\partial}{\partial x_j}(u_j \tau_{\mathrm{p}}) = \frac{\partial}{\partial x_j}\left(\Gamma \frac{\partial \tau_{\mathrm{p}}}{\partial x_j}\right) + 1, \tag{5}$$

where u is velocity; Γ is diffusion coefficient. The subscript j can be 1, 2 and 3, representing the axis of x, y and z respectively. The repeated j in one term represents the summation of the directions of the three axes. Eq. (5) can be solved with the continuity, momentum, energy and species equations to acquire the air age in a ventilated room. Numerical method is testified as an effective method by comparing the air age distribution gotten through tracer gas method and numerical method[12,14,15—17]. However, numerical method can be adopted only in single room because of computational capacity.

2 Algorithm of air age in central ventilation system

A systematic sketch of typical central ventilation system is shown in fig. 1. The system consists of air handling unit (AHU) and ducts. Fresh air comes from fresh air duct, mixed with return air coming from mixing duct, flows into ventilated room, and then leaves the room from return air duct. Part of the return air mixes with fresh air, and the rest is exhausted from exhaust air duct. The airflow in the system can be studied in four basic cases: (i) airflow in the duct without branches; (ii) airflow is divided into several streams along forked ducts; (iii) mixing of several airflow streams; (iv) airflow in ventilated room which may involve multiple inlets and outlets. If the air supply parameters such as air age are known, the air age distribution in the room and at the outlets can be calculated numerically using computational fluid dynamics (CFD) tools[12]. For case (ii), the air age after branching is equal to that before branching. So if we can work out the calculation of air age in cases (i) and (iii), the air age distribution in the whole system can be acquired.

2.1 Fresh air age in duct

The airflow in duct without branches can be considered as a one-dimensional flow. Suppose

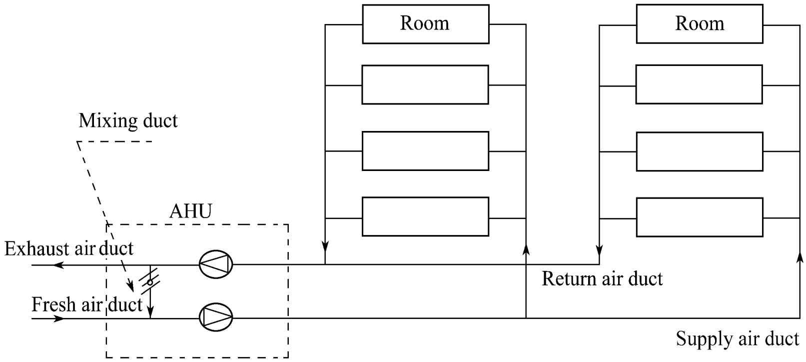

Fig. 1. Typical central ventilation system.

that the airflow velocity is u, and the length of duct is l. The transport equation of air age is

$$u\frac{\mathrm{d}\tau_\mathrm{p}}{\mathrm{d}x}=\Gamma\frac{\mathrm{d}^2\tau_\mathrm{p}}{\mathrm{d}x^2}+1. \tag{6}$$

The boundary conditions are

$$\tau_\mathrm{p}\,|_{x=0}=0, \tag{7}$$

$$\left.\frac{\mathrm{d}\tau_\mathrm{p}}{\mathrm{d}x}\right|_{x=l}=0. \tag{8}$$

In order to simplify the equations, we define the following non-dimensional parameters:

$$X=\frac{x}{l}\quad,\qquad Pe=\frac{ul}{\Gamma},\qquad \hat{\tau}_\mathrm{p}=\frac{\tau_\mathrm{p}}{\tau_\mathrm{n}}, \tag{9}$$

where τ_n is the nominal time constant, $\tau_n=\frac{l}{u}$, and Pe is Peclet number describing the ratio of convection to diffusion.

The solution of one-dimensional duct flow can be written as

$$\hat{\tau}_\mathrm{p}=X-\frac{\exp(-Pe)[\exp(Pe\,X)-1]}{Pe}. \tag{10}$$

Fig. 2 gives the non-dimensional air age distribution along the duct to clarify the influence of Pe on air age distribution. It is shown that Pe has great influence on air age. When $Pe\to\infty$, the air age $\hat{\tau}_\mathrm{p}\to X$; that is, air age is proportional to duct length, which is the case of "plug" flow.

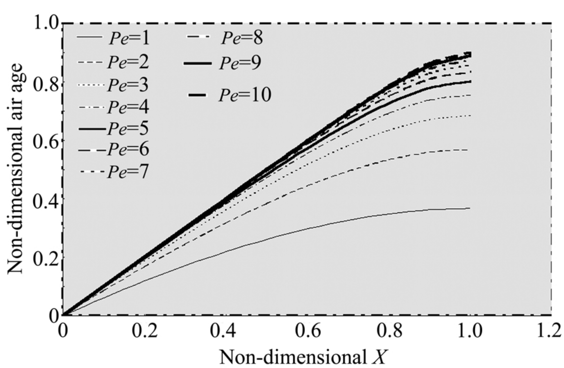

Fig. 2. The non-dimensional air age distribution along X.

By using eq. (10), the mean air age in the duct is

$$\overline{\tau} = \frac{1}{2} + \frac{(1+Pe)\exp(-Pe)-1}{Pe^2}. \tag{11}$$

Eq. (11) shows that the mean air age $\overline{\tau} \to \frac{1}{2}$ when $Pe \to \infty$, which is the case of "plug" flow. In fact, for engineering applications, the air age increase in duct can be calculated with the distance divided by the air velocity when Pe >5 as follows:

$$\tau_{\mathrm{d}} = \frac{l}{u}. \tag{12}$$

2.2 Air age in the case of airflow mixing

In the case where two airflows join together, suppose one airflow has the age of τ_1 with frequency distribution $f_1(\tau)$ and airflow volume L_1, and the other with τ_2, $f_2(\tau)$ and L_2. According to the definition, the frequency distribution of mixed air age $f_3(\tau)$ is

$$f_3(\tau) = \frac{L_1 f_1(\tau) + L_2 f_2(\tau)}{L_1 + L_2}. \tag{13}$$

The air age of mixed air τ_3 is

$$\tau_3 = \int_0^{\infty} \tau f_3(\tau)\mathrm{d}\tau = \frac{L_1\tau_1 + L_2\tau_2}{L_1 + L_2}. \tag{14}$$

When more than 2 airflows mix together, the air age τ_{mix} of mixed air can be calculated with

$$\tau_{\mathrm{mix}} = \frac{L_1\tau_1 + L_2\tau_2 + \cdots + L_n\tau_n}{L_1 + L_2 + \cdots + L_n}, \tag{15}$$

where τ_i and L_i are the air age and the airflow rate of the i th airflow to be mixed.

2.3 Algorithm for fresh air age in central ventilation system

The algorithm for fresh air age in central ventilation system is as follows (fig. 1):

(i) Calculating air age of fresh air before mixing with return air using eq. (12).

(ii) Estimating the air age of return air before mixing with fresh air; calculating the air age of mixed air using eq. (14).

(iii) Calculating the air age for every inlet opening by eq. (12).

(iv) Calculating the air age distribution and air age at outlets in every ventilated room using CFD tool[12].

(v) Calculating air age of return air using eqs. (12) and (14) or (15).

(vi) If the calculated air age of return air is close to the estimated return air age with acceptable error, stop; otherwise, use calculated air age as new estimated data and come back to step (3), until convergence researches.

In fact, iteration process is not necessary. If the ventilation is steady, the air age difference between return air and mixing air will be constant. Therefore, we can get the final results only using CFD tools once as follows:

Denote the fresh air ratio (fresh air volume divided by supply air volume) by f, fresh air age by τ_1 and return air age by τ_2 at the air mixing point, and mixed air age by τ_3. Then in the steady case we have

$$\begin{cases} \tau_3 = f\tau_1 + (1-f)\tau_2, \\ \tau_2 = \tau_3 + C. \end{cases} \tag{16}$$

Constant C is expressed as

$$C = f(\tau_2 - \tau_1). \tag{17}$$

Let the age of return air be τ_{R1}, and the mixed air age be τ_3^*. Then after the first step of iteration, we have

$$\tau_3^* = f\tau_1 + (1-f)\tau_{R1}. \tag{18}$$

According to the steps mentioned above, we can get the new age of return air τ_{R2}. The air age difference C between return air before mixing with fresh air and mixed air can also be expressed as

$$C = \tau_{R2} - \tau_3^*. \tag{19}$$

When iteration reaches its convergence, according to eq. (17), we have

$$C = f(\tau_R - \tau_1), \tag{20}$$

where τ_R is return air age, namely the τ_2 mentioned before. With eqs. (18)—(20), we can get the actual return air age

$$\tau_R = \tau_{R1} + \frac{1}{f}(\tau_{R2} - \tau_{R1}). \tag{21}$$

The actual fresh air age τ_P at an arbitrary point (including points in room) beyond AHU can be calculated with the following equation:

$$\tau_P = \tau_{P1} + \frac{1-f}{f}(\tau_{R2} - \tau_{R1}), \tag{22}$$

where τ_{P1} is the air age at an arbitrary point beyond AHU when the age of return air is estimated as τ_{R1}.

3 Case study and discussion

One central ventilation system (fig. 3), which involves 10 offices ventilated by the same AHU in a commercial building in Beijing, China is studied in this paper. All the offices have the same size and airflow rate. Each office has 2 inlets and 2 outlets, and a fresh air ratio of 25%.

As mentioned above, firstly, return air age is estimated. The air age at inlets are obtained by one-dimensional air flow characteristic, i.e. eqs. (12). Secondly, the air age distribution in ventilated rooms and at outlets is solved by CFD tools. Thirdly, the return air age is obtained by one-dimensional flow characteristic, i.e. eq. (12), and air-mixing characteristic, i.e. eq. (15). Finally, the actual fresh air age distribution is acquired by eq. (22).

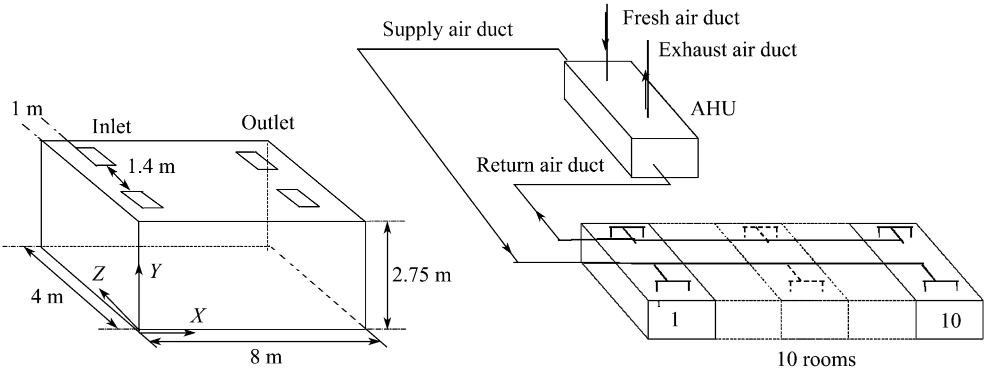

Fig. 3. Central ventilation system and ventilated rooms.

The CFD tool used is STACH-3, developed by Li et al. at Tsinghua University. STACH-3 can calculate not only the velocity, temperature and concentration distribution, but also air age and humidity distribution. The effectiveness of STACH-3 has been validated by its application in research and engineering[11—14]. The calculated fresh air age is shown in fig. 4.

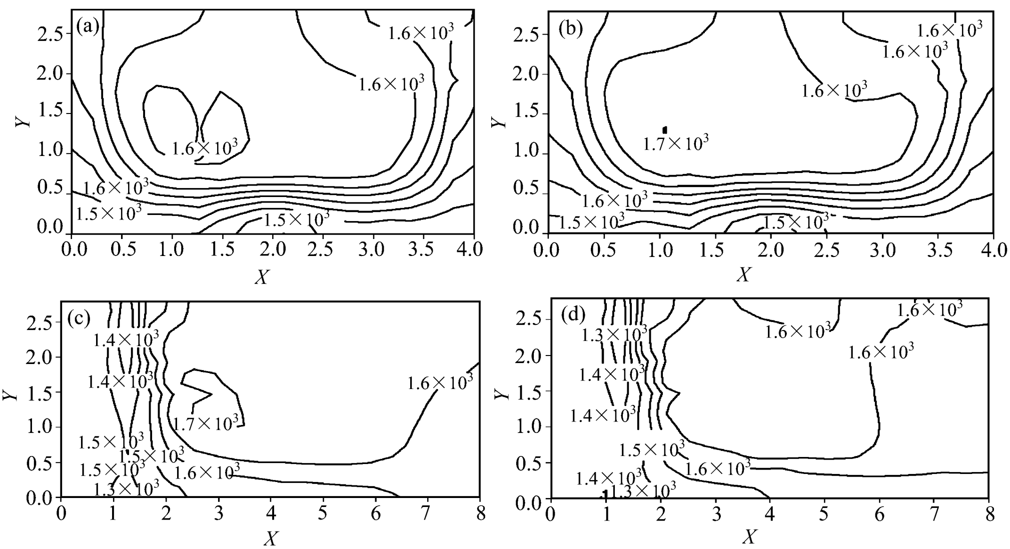

Fig. 4. Fresh air age distribution in rooms.

Fig. 4 shows that the fresh air age distributions are different in different rooms whose shape and ventilation are the same. This is because the locations of room connection to ducts are different. The air age distribution with traditional method, which simplifies the air age at inlets to zero is also obtained as those in fig. 5. Comparing fig. 4 with fig. 5, we can find that there is great difference between fresh air age distribution calculated by our method and that by traditional method because of the influence of return air and duct configuration, indicating that it is unreasonable to simplify the fresh air age at inlets into zero.

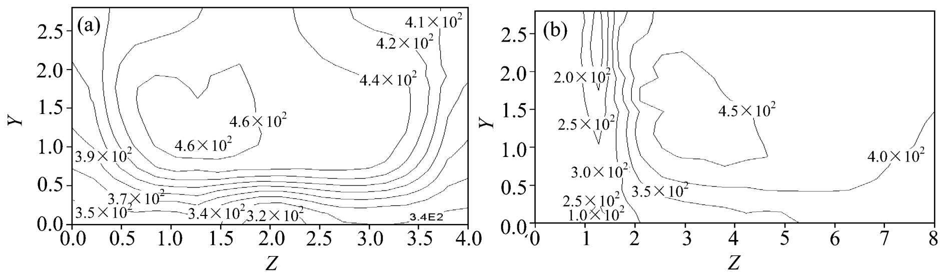

Fig. 5. Fresh air age distribution in room when air age at inlets is assumed to be zero.

4 Conclusions

Fresh air age is an important index of evaluating indoor air quality, which has the same importance as temperature and humidity concerned about traditionally. Fresh air age was measured conventionally by tracer gas technique, which is both time-consuming and expensive. On the other hand, numerical method is limited to the cases of only one room, with no return air, nor air mixing. By analyzing the air age distribution of one-dimensional flow and air mixing, this paper proposes an iteration method and a direct method to get the fresh air age in ventilation system involving return air and air mixing. We can draw following conclusions:

(1) When *Pe* number is greater than 5, the airflow in duct can be simplified into a “plug” flow. The air age can be calculated by dividing the distance to air velocity.

(2) When several airflows get mixed, the mixed air age is the average of air age of every airflow with air volume as the weight.

(3) The fresh air age distribution in the systems with return air can be obtained by one correction after calculating the fresh air age distribution in whole system based on an estimated return air age.

(4) The case study indicates the algorithm of this paper has fine feasibility and can be adapted to various branch ventilation systems.

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References

1. Zhu, N., Wang, K. H., Tian, Z., Characteristic analysis of air conditioning systems in sick buildings, HV&AC (in Chinese), 1999, 29(2): 11—15.
2. Ma, R. M., International development in research of indoor air quality in non-industrial buildings, HV&AC (in Chinese), 1999, 20(2): 38—41.
3. Li, X. T., Yang, J. R., Wang, X., Status and development of indoor air quality research, HV&AC (in Chinese), 2000, 39(3): 36—40.
4. Dorgan, C. E., Productivity link to the indoor environment estimated relative to ASHRAE 62-1989, in Proceedings of Health Buildings’94, Budapest, 1994, 461—472.

5. ASHRAE STANDARD 62-89: Ventilation for Acceptable Indoor Air Quality, 1989.
6. David, W. B., Indoor Air Quality and HVAC Systems, Berlin: Lewis Pub., 1993, 12—20.
7. CIBSE Guide: Installation and Equipment Data, London: CIBSE, 1986.
8. Sandberg, M., Sjoberg, M., The use of moments for assessing air quality in ventilated rooms, Building and Environment, 1983, 18(4): 181—197.
9. Li, X. T., Wang, X., Li, X. F. et al., Investigation on air age in a ventilated room with tracer gas technique, HV&AC (in Chinese), 2001, 31(4): 79—81.
10. Koskela, H. K., Rolin, I. E., Norell, L. O., Comparison between forced displacement and mixing ventilation in a garage, ASHRAE Transactions, IN-91, 18(7): 1119—1126.
11. Li, X. T., Wang, X., Li, X. F., Investigation on the relationship between flow pattern and air age, in Sixth International IBPSA Conference-Building Simulation'99, Kyoto, Japan, 1999, 423—429.
12. Li, X. T., Jiang, Y., Calculating air age in a ventilated room with CFD method, Journal of Tsinghua University (Sci. & Tech.) (in Chinese), 1998, 38(5): 28—31.
13. Li, X. T., Li, X. F., Zhu, Y. X., The mathematical modeling of air age, in International Symposium on Air Conditioning in High Rise Buildings'97. Sept. 9—12, 1997, Shanghai, 241—246.
14. Li, X. T., Wang, X., Li, Y., Numerical method for air age calculation in ventilated room, Building Energy & Environment (in Chinese), 1999, 18(1): 2—5.
15. Yuan, X. X., Chen, Q. Y., Glicksman, L. R., Performance evaluation and development of design guidelines for displacement ventilation, Final Report to ASHRAE TC5.3-Room Air Distribution on ASHRAE Research Project-RP-949.
16. Yang Jia, Wu Xiangsheng, The research of the numerical simulation of the age-of-air., in Proceeding of the 4th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Hong Kong: City University of Hong Kong, 2001, 339—345.
17. Awbi, H. B., Karimipanah, T., A comparison between three methods of low-level air supplies, in Proceeding of the 4th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Hong Kong: City University of Hong Kong, 2001, 311—316.