Improved calculation method of age distribution of supply air inside room with HVAC system with returning air
—— Theory and measurement example

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1. Introduction

The local mean age of air is well known and widely used as one of the important parameters in assessing ventilation effectiveness and air distribution phenomena[1,2]. The age of air was defined as the time required for supply air to reach an arbitrary point in a space from supply inlet. Since, there are multiple paths from an inlet to a point, local mean age, the average time for air to travel from an inlet to any point, is widely used. Actually, some experiments have been conducted to make evaluation of air-conditioning system by means of local mean age of air[3,4]. This paper presents the improved calculation method of age distribution of supply air inside room with HVAC system with returning air. The measurements were performed using the improved tracer gas step-up method.

2. Measurement method

Injecting some tracer gas to experimental room and measuring the consequent concentration change is an effective way to estimate local mean age of air. Typically, three injection methods are widely used: pulse method, tracer gas step-up method and step-down method.

Tracer gas step-up method makes a certain amount of tracer gas be injected from the inlet duct and reaches a steady state. The concentration response at a monitoring point is observed continuously. The concentration is maintained at the steady state value, when steady state is reached. Tracer gas step-up method is one of the effective ways to estimate local mean age of air with HVAC system without returning air. However, it is not applicable in some air-conditioning system with returning air. Therefore, we proposed the improved calculation method of local mean age of air based on tracer gas step-up method.

In some air-conditioning system with returning air, the tracer gas injected from the inlet will return back to the air supply inlet via the return louvers and then be injected again, therefore, the tracer gas concentration in the experiment room varied with time, schematic diagram of air flow direction is shown in Fig.1. As a result, even though we inject constant flow of tracer gas into experimental room, final gas concentration from inlet is neither pulse nor constant flow due to the return air.

To solve this problem, we inject tracer gas with concentration of Cs(t) from diffusers and measure gas concentration Cp(t) of monitoring P. And then, estimate pulse response Rp(t) at a monitoring point based on tracer gas concentration from inlet Cs(t) [ppm] and the measured concentration in the point Cpm(t) [ppm]. Finally, local mean age of air at monitoring point P can be calculated by the least square method. The calculating flow chart of local mean age of air is shown in Fig.2.

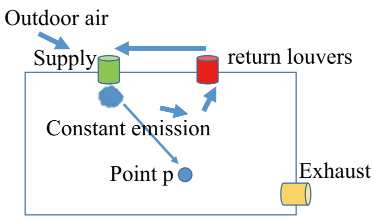


Fig. 1 Schematic diagram of air flow direction

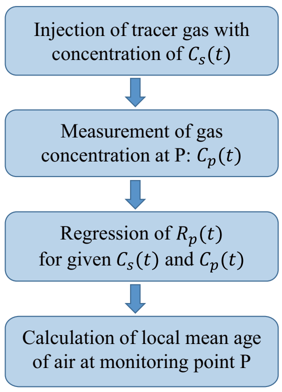


Fig. 2 Calculating flow chart of local mean age of air

Assuming that if we inject a unit pulse of tracer gas, the measured gas concentration of point P is Rp(t), namely, the unit response function. Similarly, if a small amount M of tracer gas was injected, the measured concentration Cp(t) should be:

$$C_p(t) = \int_0^{\infty} M(t-\tau)R_p(\tau)d\tau = \int_0^{\infty} Q \cdot C_s(t-\tau)R_p(\tau)d\tau \qquad (1)$$

However, if no constraints given, in some cases the problem above is an ill-posed problem. What's more, sometimes, Rp(t) result is unreasonable, e.g. Rp(ti)<0 for some i is never acceptable because there is no minus concentration in real world.

In order to solve this, we assume an reasonable model of Rp(t) as below:

$$Rp\,(t) = \begin{cases} b \cdot e^{-c(t-a)} & t>a \\ 0 & t<=a \end{cases} \tag{2}$$

Then minimizing the following error function with constraints will give us the best Rp(t). After the calculation of Rp(t), according to Eq (3). The best response factor a was manually selected, then b and c were determined by solver in EXCEL, local mean age of air τ_p at an arbitrary point P can be easily obtained.

$$\tau_p = \frac{\int_0^{\infty} tR_{p(t)}dt}{\int_0^{\infty} R_{p(t)}\,dt} \tag{3}$$

M [m^3/h] : emission rate of tracer gas
Rp(t)[$1/m^3$]: unit response function
Cp(t) [m^3/m^3] : concentration of point P
Cs(t) [m^3/m^3] : concentration of supply air
τ_p [h] : local mean age of air at point P
Q [m^3/h] : airflow rate
a, b, c[-]: constant

3. Measurement example

Experiments were conducted in the showroom of KIMURA KOHKI Corporation conditioned by ceiling induction diffusers. In this type of air conditioning system, the air disposed by air-conditioning enters the air supply chamber, and be sprung out at a speed of 3~5m/s through banding nozzle. Accordingly, as a result of the negative pressure of induction chamber, indoor air is induced and mixed with the primary air, as shown in Fig.3. The proportion of indoor air is 40%, and the primary air accounts for 60% in total mixed air. For example, when the temperature of indoor air and supply air is 26 ℃ and 13 ℃ respectively, the mixed air temperature will be 18 ℃ , the weighted average of indoor air and supply air temperature. Then the mixed air is rectified and blown out at initial speed of 0.2~0.8m/s, through the rigid diffusion fins installed on aluminum inlet plate.

The test period extended over 19 days from November 2nd~20th, 2015. The dimensions of experimental room were 7.35m(d)×5.35m(w)×2.42m(h), as shown in Fig. 2 and Fig. 3. Both the north wall and east wall were insulated with polystyrene foam. Two square return louver (275mm×275mm) of VHS were arranged in the corner of ceiling, and four rectangular supply inlets (1200mm×500mm) with induction panel were located on ceiling above beds (one for each bed). Moreover, the exhaust opening was a crevice, which located between the door and the floor. The size of exhaust opening was 865mm×7mm. The airflow rate from each air conditioner was 213m^3/h, respectively, where the airflow rate of outdoor air and return air were 50m^3/h and 163m^3/h.

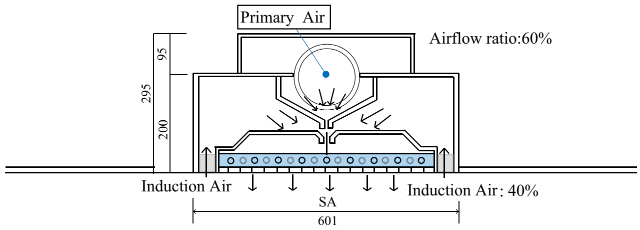


Fig. 3 Air-conditioning system with induction panel

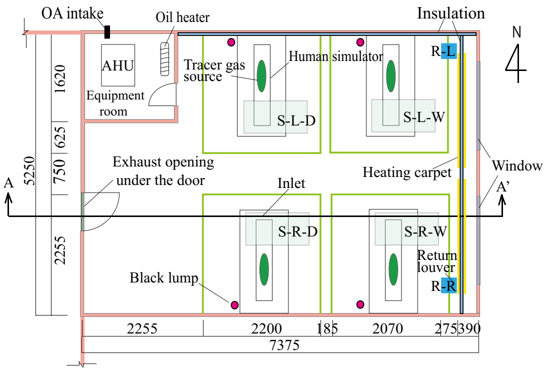


Fig. 4 Plan of experimental room [mm]

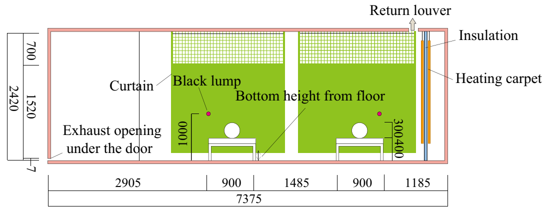


Fig. 5 A-A' section of experimental room [mm]

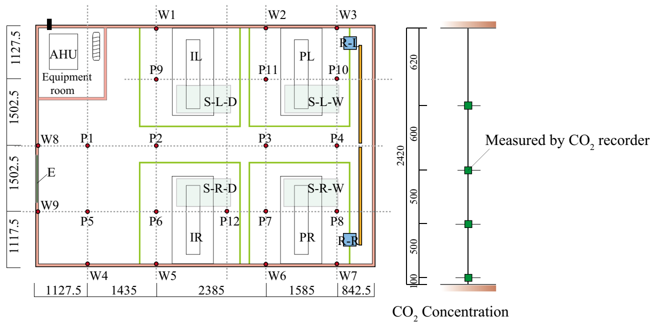


Fig. 6 Measurement points of experimental room [mm]

3.1 Measurement instruments

The outdoor air was heated by the oil heater in the experimental room, accordingly, the outdoor air temperature rose to 32 ℃ . The spiral duct (φ150mm, H1500mm) with PVC coating heating-cable was used as human simulator. Heat generation rate of each human simulator was 40W as sensible heat load of patient. Black lamp was set aside of each bed at the height of 1000mm above ground for the simulation of heat generated by home appliance such as TV and refrigerator. The power of each lamp was 90W. There were four pieces of heating carpets which were pasted on the both side of polyethylene foam used as heat gain from windows, and the thickness of the set was

5mm. The heat flux of heating carpets was 1000W in total. In addition, the power of illumination in the laboratory was 230W totally. CO_2 as tracer gas was injected from the inlet. Total flow rate of CO_2 was restricted at $1.5L \cdot min^{-1}$ by mass flow meter. The measurement points of CO_2 concentration were given in Figure 6. There were 10 straight poles set in the laboratory and CO_2 concentration was measured at 4 points vertically, at four heights of each pole (100mm, 600mm, 1100mm and 1700mm), i.e. 40 points for all. Concentration were collected using CO_2 recorders (TR-576, TR-76Ui, T&D Corporation). Then every 30 seconds, the instantaneous value was recorded with the measuring instruments.

3.2 Experimental procedures

When the indoor air temperature and wall surface temperature has reached steady state, tracer gas is injected from the inlet. Then, CO_2 concentration is measured after the steady state being confirmed.

3.3 Analysis

Here, we list some sets of result for analysis. Experiments had been conducted by changing two parameters: dosing positions of tracer gas (simulating contaminant), with or without curtain around beds. Experimental conditions of cases mentioned in this paper were shown in Table 1.

Table 1. Experimental conditions

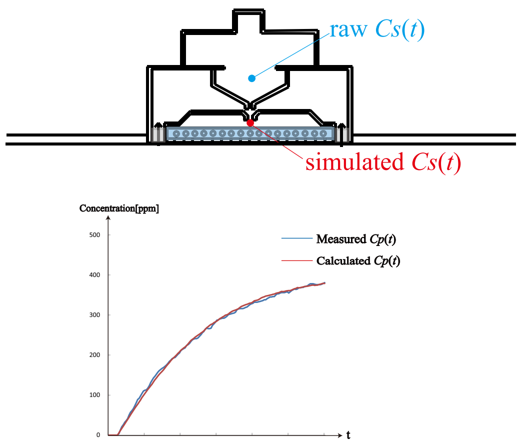
Item	Condition	Air change rate [$1 \cdot h^{-1}$]	Positions of tracer gas generation	Curtains around bed
Case 1	2-PD-NC	2	PD	Open
Case 2	2-ID-NC		ID	Open
Case 3	2-PD-C		PD	Shut
Case 4	2-4D-NC		4D	Open

PD: perimeter diffuse ID: interior diffuser 4D: four diffusers

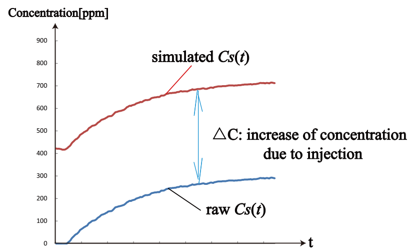
First of all, we should eliminate the influence of primary air. All Cp(t) and Cs(t) should subtract their original value. However, such subtraction will eliminate injected CO_2 of Cs(t) at the same time, therefore, the amount of CO_2 injection should be added to Cs(t). The final simulated Cs(t) is shown as Fig. 7a), a sample error minimization result was shown in Fig. 7b) and the corresponding Rp(t) result was shown in Fig. 7c). While, the chang of measured concentration under constant emission of CO_2 at supply inlets is shown in Fig. 7d).

The diagrams (Fig.8-Fig.10) showed vertical profile of local mean age of air distribution with height.

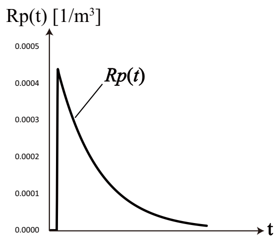
In cases where CO_2 emitted at perimeter diffuse (PD) and interior diffuse (ID) respectively, e.g. case 1 and case 2, the air change rate were set at 2 times•h^{-1} without curtain around the bed were shown in Fig. 8. In case 1 (black), the P1, P2, P5 and P6, which are far away from inlet has the minor variation of air age result, while, in P3, P4, P7 and P8, the variation is much higher because of their short distances from the inlet. Similar phenomenon can also be found in case 2. The variation of P6 is



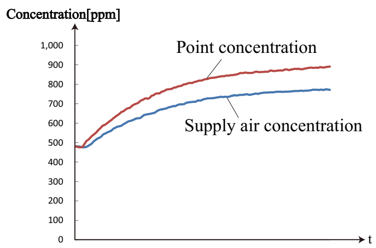
a) An example of concentration curve



b) Injected tracer gas from supply



c) An example of pulse response Rp(t)



d) An example of supply air and point P concentration

Fig.7 Change of concentration and response function

the largest because of its short distance with inlet ID, and with distance increasing, the variation also decreases. Such result can be explained by the reason of multiple paths. Tracer gas usually travels in different paths, in the area near the inlet, due to the complex air flow, the distance of different path varies heavily which cause the huge variation of local mean air age in this area.

Fig. 9 demonstrated the results of case 1 (red) and case 3 (black) with and without curtain respectively. As shown in the figure,

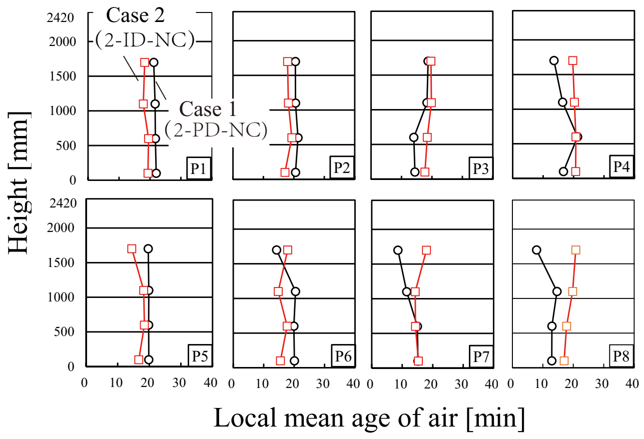


Fig. 8 Local mean age of air
(contaminant source position:PD and ID, without curtain, air change rate: 2 times·h^{-1})

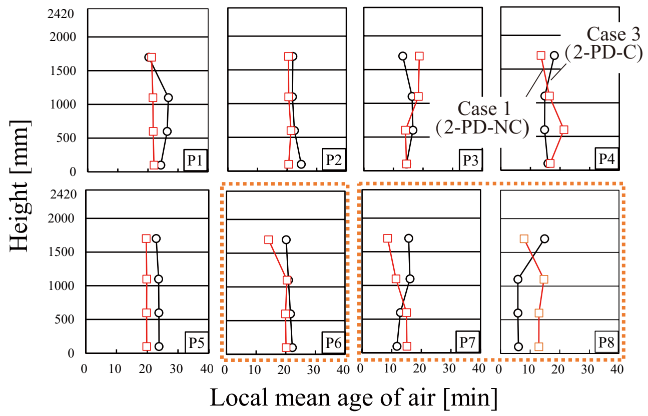


Fig. 9 Local mean age of air
(contaminant source position:PD, with and without curtain, air change rate: 2 times·h^{-1})

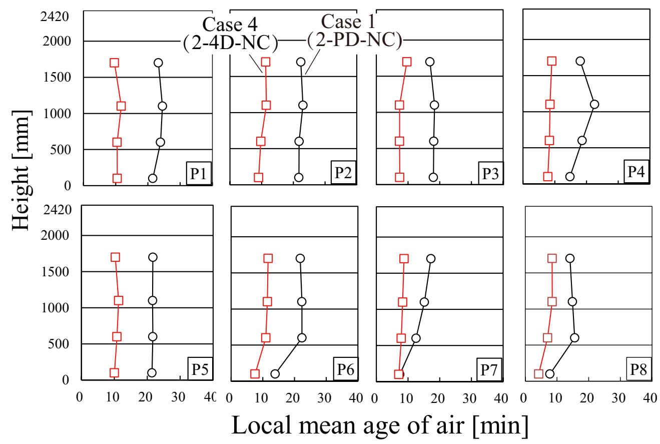


Fig. 10 Local mean age of air
(contaminant source position:PD and 4D, without curtain, air change rate: 2 times·h^{-1})

there were huge differences in the local mean age of air results between these two cases in P3, P4, P7 and P8. That difference is due to the influence of the existence of curtain, more specifically, the existence of curtain changes some paths of airflow, thus resulting in a different local mean age of air.

If the premise of the other conditions fixed, the experiments were carried out by changing dosing positions of tracer gas from perimeter diffuser to four diffusers. Fig. 10 provided the results of case 1 (black) and case 4 (red). As shown in the figure, there were huge differences in the local mean age of air results between these two cases in P1~P8. We can see that the local mean age of air when simulating contaminant is injected from four diffusers is smaller than that injected from perimeter diffuser. That difference is due to the influence of dosing positions, the distance from contaminant to monitoring point, results in a different local mean age of air.

4. Conclusion

Though tracer gas step-up method is one of the effective ways to estimate local mean age of air in some air-conditioning system, it is not applicable in HVAC system with returning air. Therefore, the improved calculation method of local mean age of air based on tracer gas step-up method is provided. The method has definite physical meaning, and numerical example checked the validity and precision of the improved method. However, in this paper, we calculate the local mean age of air uesd by the least square method based on the convolution theory.

In the future, deconvolution method will be used to calculate the unit response function Rp(t). And then the optimal mathematical models of response function Rp(t) will be established by making comparison of various mathematical models. Thus, more precise results will be obtained.

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