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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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:

\[
C_p(t) = \int_0^m M(t - \tau)R_p(\tau)d\tau = \int_0^m Q \cdot C_s(t - \tau)R_p(\tau)d\tau
\]  

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.
3. 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

\[
R_p(t) = \int_0^t b \cdot e^{-c(t-a)} \, dt = \frac{b \cdot e^{-c(t-a)}}{c} \quad t < a
\]

Then minimizing the following error function with constraints will give us the best \( R_p(t) \). After the calculation of \( R_p(t) \), 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 \( \tau_p \) at an arbitrary point \( P \) can be easily obtained.

\[
\tau_p = \frac{\int_0^t \tau_p \, dt}{\int_0^t R_p(t) \, dt}
\]
5mm. The heat flux of heating carpets was 1000W in total. In addition, the power of illumination in the laboratory was 230W totally. CO2 as tracer gas was injected from the inlet. Total flow rate of CO2 was restricted at 1.5L·min\(^{-1}\) by mass flow meter. The measurement points of CO2 concentration were given in Figure 6. There were 10 straight poles set in the laboratory and CO2 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 CO2 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, CO2 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

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
<th>Air change rate ([1\cdot h^{-1}])</th>
<th>Positions of tracer gas generation</th>
<th>Curtains around bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>2-PD-NC</td>
<td>2</td>
<td>PD</td>
<td>Open</td>
</tr>
<tr>
<td>Case 2</td>
<td>2-ID-NC</td>
<td>2</td>
<td>ID</td>
<td>Open</td>
</tr>
<tr>
<td>Case 3</td>
<td>2-PD-C</td>
<td>2</td>
<td>PD</td>
<td>Shut</td>
</tr>
<tr>
<td>Case 4</td>
<td>2-4D-NC</td>
<td>2</td>
<td>4D</td>
<td>Open</td>
</tr>
</tbody>
</table>

PD: perimeter diffuse  ID: interior diffuse  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 CO2 of Cs(t) at the same time, therefore, the amount of CO2 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 CO2 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 CO2 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 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,
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 used 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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References

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