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USE OF MACROSCOPIC FLOW NUMBER FOR ASSESSING SPACES WITH MECHANICAL VENTILATION

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ABSTRACT

The performance of the mechanical ventilation system in large spaces is proposed to be evaluated by macroscopic numbers describing the air flow. This includes the air changes rate per hour, the air change rate per hour per floor area, the momentum jet number, and the nominal time constants. To determine which number is the best choice, experimental studies in nine big waiting halls were performed. The indoor environment in the mechanical ventilated spaces can be assessed by the measured local mean air velocity, carbon dioxide level, and local age of air. Correlations of the measured mean values of local air velocity, carbon dioxide level, and local age of air with those macroscopic flow number are investigated. It is found that the relationships of the air change rate per hour, the air change rate per hour per floor area and the nominal time constants with the mean air speed, the mean carbon dioxide concentration, and the mean local age of air were not clear. A revised momentum jet number taking the height of the diffuser into account is proposed and linear relations can be fitted empirically to correlate it with the mean air speed, carbon dioxide concentration, and the local age of air for these nine sites. It seems that this flow number can be used for evaluating the performance of the ventilation systems.

INTRODUCTION

Mechanical ventilation systems are commonly installed in large enclosed spaces for providing adequate fresh air to the occupants and removing the unwanted air contaminants within a reasonable period of time, attempting to maintain an acceptable air quality level. Many design guides on ventilation are available in literature [1-5]. Up to the present moment, there is still no unified way to assess

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the effectiveness of a ventilation system although quite a lot of works have been reported in this area. People used to ask the questions on how many air change per hour the ventilation system has to operate and what are the design criteria. Further, in designing the ventilation and air-conditioning in big enclosed spaces liked an atrium hall, a large portion of the space volume, except those at the occupancy levels, would not be ventilated or air-conditioned. Therefore, using a conventional ventilation index like the number of air change per hour per floor area is not good enough in specifying the ventilation rate of the area.

In this article, macroscopic number describing air flow is proposed to evaluate the performance of the ventilation systems in big mechanically ventilated spaces. Field studies in nine big mechanically ventilated halls are performed to justify this proposal. The mean air speed, carbon dioxide concentration, and the local age of air are measured in different positions to determine the indoor environment with respect to ventilation. Macroscopic flow numbers proposed are the air change rate per hour, the air change rate per hour per floor area, the jet momentum number J, and the nominal time constant τ_n. A revised jet momentum number J* with the height of the supply air outlets taken into account is defined for describing the air flow. Correlations of the mean air speed, mean carbon dioxide concentration, and the mean local age of air among those macroscopic flow numbers are investigated to see which can assess the ventilation system.

EXPERIMENTS

Field measurements were carried out in nine big halls which are mechanically ventilated either through forced extraction or fresh air supply. Detailed description on the experimental works had been reported elsewhere [6]. The mean air speed, carbon dioxide concentration, and age of air were measured at twelve to thirty positions at each site to determine the indoor environment with respect to ventilation. The number of measuring points depended on the size of the test sites. At each position, measurements were taken at 1.45 m above the floor level and with a five-minutes period for recording the data. This height of measurement was considered appropriate for the type of activity within the halls. The ventilation air flow rates at the supply air outlets were also measured. A summary on the relevant data such as the size of the test sites and the number of measurement positions is shown in Table 1.

The air flow in the ventilated space is turbulent [7], and the instantaneous velocity V(t) is expressed as a sum of the mean velocity u and fluctuation v′. The mean velocity u is the average of the instantaneous values over an interval from time t_0 to t_0+t_1:

$$u = \frac{1}{t_1}\int_{t_0}^{t_0+t_1} V(t)dt \tag{1}$$

Table 1. Summary Information of the Test Sites

Test Site	Length L/m	Width W/m	Height H/m	Height of Diffuser h/m	Floor Area A_{Room}/m^2	Volume of Room V_{Room}/m^3	No. of Measuring Points	Air Speed at 1.45 m Above Floor Level u/ms^{-1}		Air Diffuser Velocity u_{dm}/ms^{-1}	
								Mean	*SD*	Mean	*SD*
A	61	25.2	20	10	1537	30744	30	0.45	0.12	4.79	0.22
B	71.5	15.1	8	4.9	1080	8637	20	0.23	0.08	3.02	0.09
C	46.8	20.5	5.7	3.4	960	5468	20	0.25	0.08	3.47	0.12
D	76.2	12.6	4.7	4.7	960	4512	15	0.46	0.25	5.07	0.33
E	60	13.5	5.7	4.4	810	4617	20	0.35	0.07	4.65	0.18
F	19.3	42	8	4	810	6484	20	0.44	0.11	4.78	0.16
G	23.8	21	5	5	500	2499	20	0.22	0.10	3.47	0.12
H	26.7	15	8	4.8	400	3204	15	0.27	0.10	3.46	0.21
I	20	15	7.7	4.6	300	2310	15	0.37	0.19	3.78	0.18

Test Site	Carbon Dioxide Concentration $\overline{C}_{CO_2}$/ppm		Local Age of Air A_m/s		Ventilation Flow Rate Q/m^3s^{-1}	Air Change Rate Per Hour ACH/hr^{-1}	Air Change Rate Per Hour Per Floor Area $AC_f/\times 10^{-2}$ ACH m^{-2}	Jet Momentum Number J ($\times 10^{-6}$)	Revised Jet Momentum Number J^* ($\times 10^{-6}$)	Nominal Time Constant τ_n/s
	Mean	*SD*	Mean	*SD*						
A	496	19	30	5	40.3	4.72	0.31	641	1281	763
B	547	5	72	12	7.9	3.29	0.30	282	460	1093
C	555	15	60	7	11.8	7.76	0.81	764	1281	463
D	494	28	76	10	8.5	6.78	0.70	974	974	531
E	469	9	27	4	14	10.91	1.35	1439	1864	330
F	472	5	24	8	9.3	5.16	0.64	700	1399	697
G	590	22	60	6	5.3	7.63	1.53	751	751	472
H	479	13	39	7	3.7	4.16	1.04	408	680	866
I	497	19	40	8	3.8	5.92	1.97	635	1062	608

Similarly, the mean carbon dioxide concentration is given by:

$$\overline{C}_{CO_2} = \frac{1}{t_1} \int_{t_0}^{t_0 + t_1} C_{CO_2}(t)dt \qquad (2)$$

Both of the above parameters were measured using a Bruel and Kjaer indoor climate analyzer 1213. The age of air was measured using the tracer gas concentration decay method with a Bruel and Kjaer multigas monitor type 1302 with sulphur hexafluoride SF_6. The age of air A_i at the i^{th} location is calculated by the expression:

$$A_i = (t_{stop} - t_{start})C_{av}/Ct_{start} \qquad (3)$$

where t_{start} is the time when tracer injection is stopped at the beginning of a tracer gas decay; t_{stop} is the time of the final tracer gas measurement at location i during the tracer gas decay; C_{av} is the time average tracer gas concentration at location i between time t_{start} and t_{stop}; and Ct_{start} is the tracer gas concentration at location i at time t_{start}.

A summary of the mean values of the mean air speed u, mean carbon dioxide concentration $\overline{C}_{CO_2}$ and mean values of local age of air A_m is shown in Table 1.

MACROSCOPIC FLOW NUMBERS

The total ventilation rate Q (m^3s^{-1}) of the site was calculated by summing the product of the air speeds and the area at the diffusers:

$$Q = \sum_{1}^{n=i} u_{di}A_{di} \qquad (4)$$

where u_{di} is the mean face velocity of the i^{th} diffuser and A_{di} is the face area of the i^{th} diffuser.

The air exchange rate (in number of air change per hour) ACH is given by:

$$ACH = \frac{Q \times 3600}{V_{Room}} \qquad (5)$$

The air change rate per hour per floor area AC_f (ACH m^{-2}) was calculated by dividing ACH by the floor area of the room A_{Room} (m^2):

$$AC_f = \frac{ACH}{A_{Room}} \qquad (6)$$

The jet momentum number J is proposed by Barber et al. [8, 9] to be set as a design criterion for air diffuser system. This is calculated from the total ventilation flow rate Q(m^3s^{-1}), mean air diffuser velocity u_{dm} (ms^{-1}) which is the average air face velocity over the diffuser, the acceleration due to gravity g (9.8 ms^{-2}) and the volume of the room V_{Room} (m^3):

$$J = \frac{Qu_{dm}}{gV_{Room}} \tag{7}$$

The modified jet momentum number J* is calculated by taking the height of diffuser into account.

$$J^* = \frac{Qu_{dm}}{gA_{Room}h} \tag{8}$$

where h is the height of the center line of the supply air jet from the finished floor level (m).

Another parameter measured is the nominal time constant τ_n (5) which was calculated by [10, 11]:

$$\tau_n = \frac{V_{Room}}{Q} \tag{9}$$

This quantity is related to the time duration of the fresh air discharge of the ventilation system. As discussed by Sandberg and Sjoberg [10], a brief discharge would have a duration time much shorter than the value of τ_n and a prolonged discharge would give a duration longer than τ_n. In view of equation (5), the jet momentum number is related to the nominal time constant τ_n as:

$$J = \left(\frac{u_{dm}}{g}\right)\frac{1}{\tau_n} \tag{10}$$

Plotting log (J) against log (τ_n) should give a straight line of slope –1 if the above expression is correct.

RESULTS AND DISCUSSION

Results on the mean values of the air speed u in the occupied zone, mean carbon dioxide concentration $\overline{C}_{CO_2}$, and mean local age of air A_m at the different ventilation air flow rates are shown in Table 1. Macroscopic flow numbers including the air change rate (ACH), the air change rate per hour per floor area AC_f, the jet momentum number J, the modified jet momentum number J* and the nominal time constants τ_n are shown there as well. The correlation of J and τ_n is clearly illustrated in Figure 1 by plotting $\log_e$ (J) against $\log_e$ (τ_n). In fact, the following relation with correlation coefficient of 0.926 is fitted:

$$\log_e J = -1.19 \log_e (\tau_n) + 0.30 \tag{11}$$

Taking the mean air speed u, the carbon dioxide concentration $\overline{C}_{CO_2}$ and the mean local age of air A_m as the criteria for evaluating the indoor environment

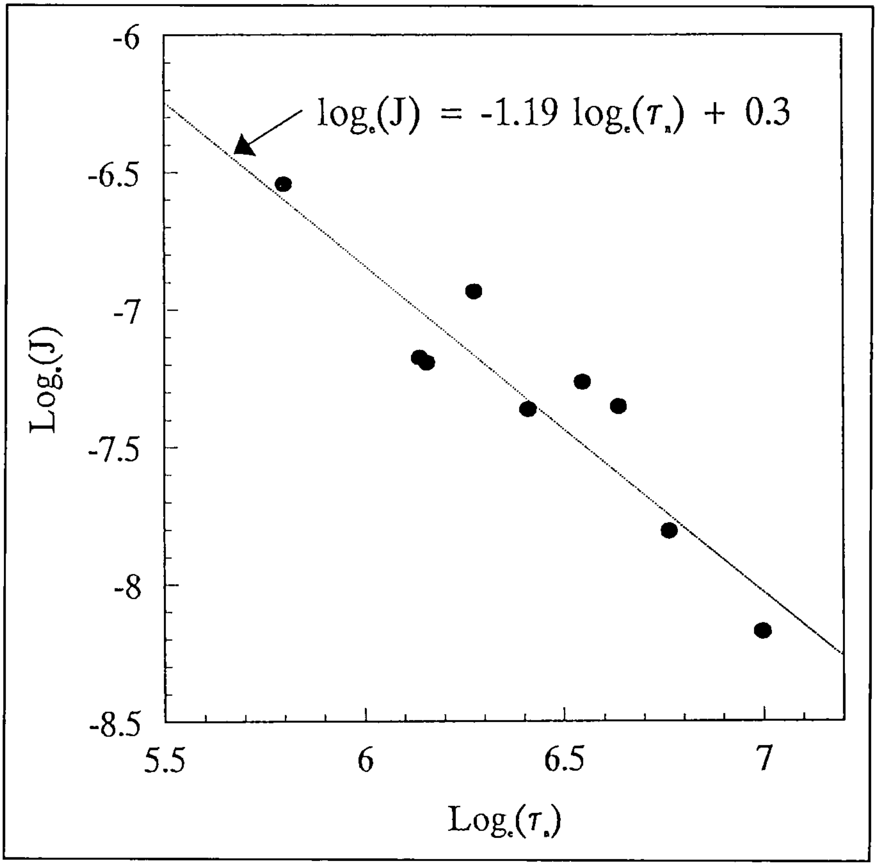


Figure 1. Log$_e$(J) against log$_e$(τ_n).

with respect to ventilation, the correlation of those quantities with the macroscopic flow numbers air change rate per hour ACH, air change rate per hour per floor area AC_f, jet momentum number J, modified jet momentum number J*, and the nominal time constants τ_n are studied. In views of Table 1, there are no clear correlation of the mean air speed, mean carbon dioxide concentration, and mean local age of air with the air changes per hour ACH, the air change rate per hour per floor area AC_f, the jet momentum number J and the nominal time constant τ_n. A typical example on the AC_f is shown from Figures 2a to 2c. The air change rate per hour per floor area is not a good flow number in specifying the performance of the mechanical ventilation system in big spaces. However, for plotting those parameters against the revised jet momentum number J* as from Figures 3a to 3c, straight lines can be fitted for the variation of J* with the mean air speed u, the

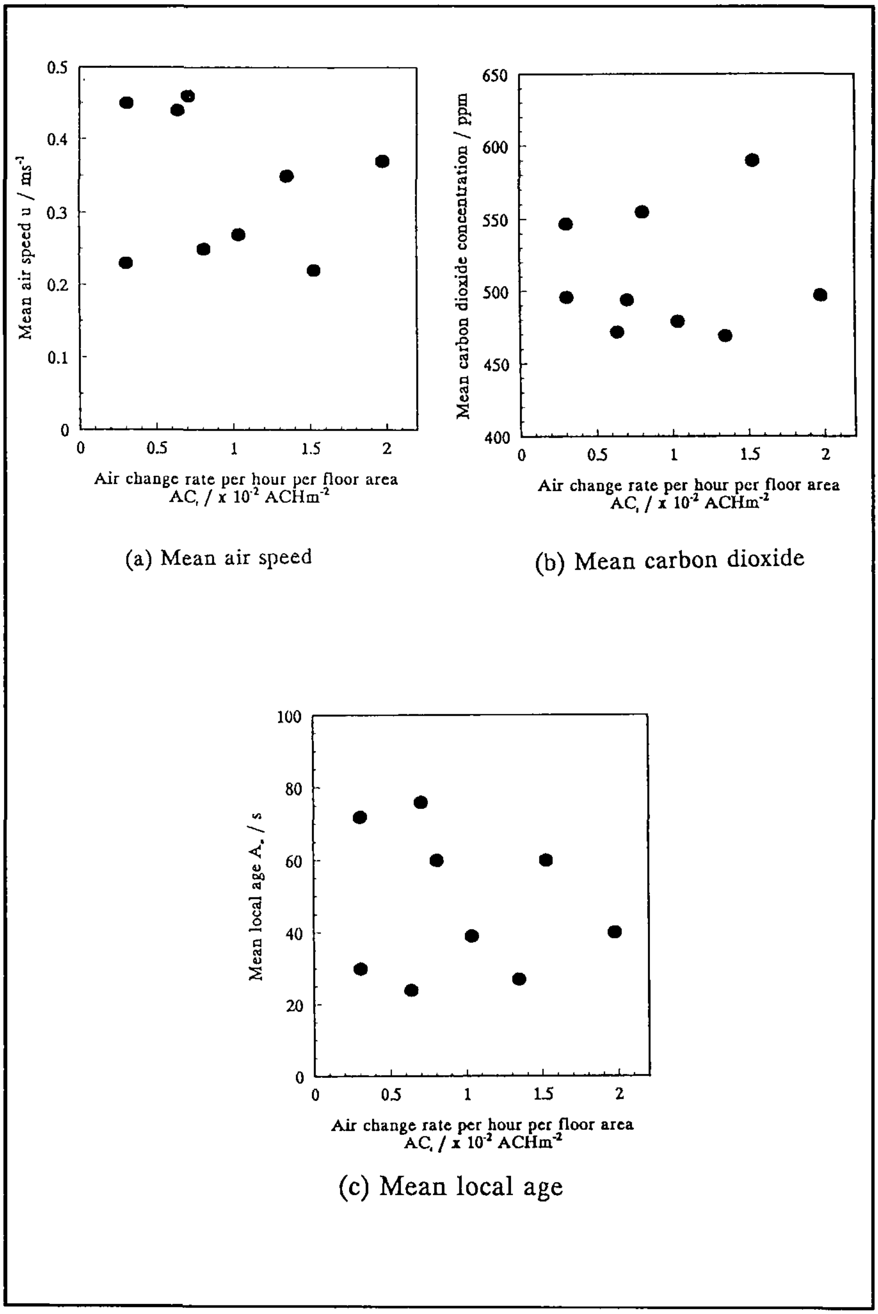
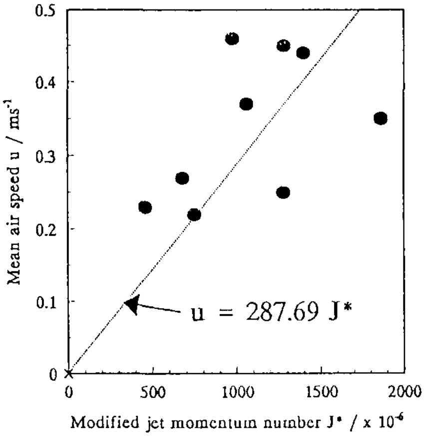
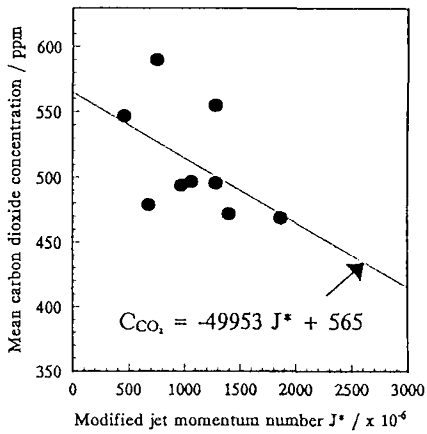


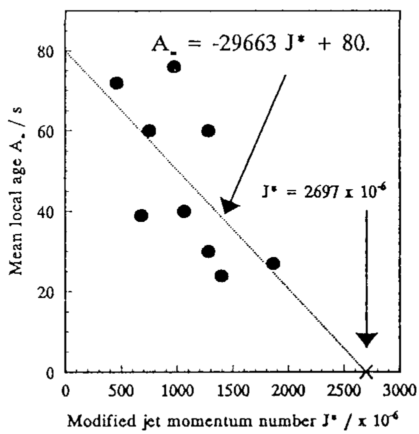
Figure 2. Variation with the air change rate per hour per floor area.



(a) Mean air speed



(b) Mean carbon dioxide



(c) Mean local age

Figure 3. Variation with the modified jet momentum number.

carbon dioxide concentration $\overline{C}_{CO_2}$ and the mean local age of air A_m with the revised jet momentum number J* as:

$$u = 287.69\ J^* \tag{12}$$

$$\overline{C}_{CO_2} = -49953\ J^* + 565 \tag{13}$$

$$A_m = -29663\ J^* + 80 \tag{14}$$

The correlation coefficients for equations (12), (13) and (14) are 0.638, 0.502 and 0.641 respectively. This means if J* is greater than 2696.96×10^{-6}, the mean local age of air will have a value approaching zero which implies very good ventilation performance. Taking equation (13) into account, the mean carbon dioxide would be 430 ppm.

CONCLUSIONS

An experimental evaluation on the mechanical ventilation system in nine large enclosed spaces was performed. The mean air speed at 1.45 m above floor level, the mean local age of air and the mean carbon dioxide concentration were used to determine the indoor environment with respect to ventilation. Macroscopic flow numbers including the air change rate per hour, air change rate per hour per floor area, jet momentum number, modified jet momentum number, and the nominal time constant were measured. Correlation studies of this group of macroscopic flow numbers with the three indoor environmental parameters were made. The air change rate per hour, the air change rate per hour per floor area and the nominal time constants are not good in describing the ventilation system. The modified jet momentum number is found to be suitable for evaluating the ventilation system used in big mechanical ventilated enclosure.

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