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Local air speeds measurement in mechanically ventilated spaces

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Abstract

Air speeds at the occupied zone were studied experimentally in seven large railway stations of space volume varying from 540–9076 m^3. The spaces are installed with mechanical ventilation systems and the air supply flow rates are from 0.455–23.67 $m^3\ s^{-1}$. Results were analyzed by dividing the measured air speeds into different ranges. Statistical data such as the peak value, mean value, range of the air speeds and the bandwidth are calculated. Values of the percentage of discomfort were calculated and analyzed similarly. Correlation relationships of the variables with the macroscopic numbers describing air flow of the space including the air exchange rate, ventilation rate, the Reynolds number and the modified jet momentum number are studied. Two additional macroscopic flow numbers X_1 and X_2 defined by considering the range covered by a diffuser discharging air with a large horizontal component are proposed. It is found that both the modified jet momentum number and the new flow number X_1 correlate with the air speed at the occupied zone and are recommended to use as an operating parameter on specifying the performance of the ventilation system for the space.

Nomenclature

A	area (m^2)
A_{di}	diffuser area (m^2)
ACH	air exchange rate (no. hr^{-1})
B, H	length and width of the cross-section perpendicular to inflow (m)
D	hydraulic diameter of the room (m)
E_{ri}	deviation between measured and predicted values for the ith pair of data (F_i, G_i)
F, G	quantative variables
$\bar{F}, \bar{G}$	sample means of F_i and G_i
g	acceleration due to gravity (9.81 m s^{-2})
h	diffuser height above floor level (m)
J	jet momentum number
J^*	modified jet momentum number
N	number of variable pairs
PD	percentage of discomfort (%)
PLC	percentage of people feeling less comfortable
Q	total ventilation flow rate ($m^3\ s^{-1}$)
R	range
Re	Reynolds number
S_d	separation distance between diffusers (m)
Tu	turbulence intensity (%)
Ta	air temperature (°C)
u	mean air speed measured at different location (m s^{-1})
$V(t)$	instantaneous air velocity (m s^{-1})
v_m	hypothetical mean air speed in a room (m s^{-1})
V_{room}	volume of room (m^3)
VR	ventilation rate per unit floor area ($m^3\ s^{-1}\ m^{-2}$)
v'	velocity fluctuation (m s^{-1})
X_1, X_2	flow numbers defined in eqns (23) and (26)
x, z	vertical and horizontal distances away from the inlet jet

Greek symbols

α	constant
ν	kinematic viscosity of air ($m^2\ s^{-1}$)
$\upsilon_{FF}, \upsilon_{GG}$	sample variances of F_i and G_i
υ_{FG}	sample covariance of F_i and G_i

Subscripts

25, 75	25 and 75 percentile
50	the median value
di	diffuser condition, of diffuser
i	ith value
max	the maximum value
mean	the mean value
min	the minimum value
R	of range
room	of room

Other symbols

$\mathfrak{R}$	correlation coefficient

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1. Introduction

Design for the minimum ventilation requirements for specific applications are provided by common ventilation design guides [1–6]. However, whether performances of systems designed according to these guides are satisfactory or not is questionable. To have a better evaluation on the performance of those ventilation systems, the air flow characteristics in the waiting area of seven large railway stations were studied [7, 8]. The space volume varied from 540–9076 m^3. The air supply flow rates were from 0.455–23.67 $m^3\ s^{-1}$, or 1.86–22.04 air changes per hour. Air speeds at the occupied zone were measured and the results are now used to evaluate the performance of the ventilation system.

Values of the air speed measured in the tests reported earlier [7, 8] were further analyzed statistically and then correlated with macroscopic flow numbers including conventional ventilation indices such as the number of air changes per hour, ventilation rate per floor area VR and others such as the Reynolds number Re and the modified jet momentum number J^*.

Two additional flow numbers X_1 and X_2 defined by considering the range to be covered by air diffusers are evaluated as well. Those are good for considering air discharged from the diffuser with a large horizontal air velocity component as most of the air diffusers used in the Hong Kong Special Administrative Region (HKSAR, formerly Hong Kong) would discharge air inclined at an angle less than 5° to the horizontal.

2. Field studies

Field measurements [7, 8] were carried out in the waiting halls of seven railway stations with mechanical ventilation. They are labelled from A–G and a summary of the sizes and mean room temperature T_{room}, the brief description of the mechanical ventilation system including the mean inlet air speed u_{di} and the inlet temperature T_{di} at each site are shown in Table 1. Measurements of the mean air speeds were made at 1.45 m above floor level during a three-minute period [5]. This height of measurement was considered appropriate for the type of activities within the railway stations. All the measurements were taken in a three month period from December 1993 to February 1994. The outdoor air temperature in this period was fairly constant. The number of measurement positions, the room temperature and supply air temperature made are shown also in Table 1. Description of the experiments is reported earlier [7, 8] and will not be repeated in here.

Since the air flow in the ventilated space is turbulent [9], the instantaneous velocity $V(t)$ can be expressed as a sum of the mean velocity u and fluctuation v'. The mean velocity u is the average of the instantaneous values over a time interval of 3 min [5]. From the measured mean velocity, macroscopic flow parameters were measured. This included the total ventilation flow rate Q (supply only) which was calculated by summing all the mean face velocity u_{di} of the ith diffuser multiplied by its free diffuser area A_{di}:

$$Q = \sum_{1}^{n=i} u_{di} A_{di} \tag{1}$$

The air exchange rate ACH (in number of air changes per hour) was calculated by the total ventilation flow rate Q over the space volume V_{room}:

$$ACH = \frac{Q \times 3600}{V_{room}} \tag{2}$$

The air exchange rates in those seven waiting halls are shown in Table 1.

Another parameter measured was the ventilation rate VR ($dm^3\ s^{-1}\ m^{-2}$) which is simply the ventilation rate per floor area A_{room}:

$$VR = \frac{Q}{A_{room}} \tag{3}$$

Values of the ventilation rates of the stations are shown in Table 1. This parameter has the same problem as the air exchange rate in assuming perfect mixing in the room. In designing a ventilation system for a high headroom atrium, using the ventilation rate might be better than the air exchange rate as the floor area of the room is included. But the mean air speed in the occupied zone might not be increased by using a higher ventilation rate.

Another parameter measured is the Reynolds number (Re) which is given by:

$$Re = \frac{v_m D}{\nu} \tag{4}$$

where ν is kinematic viscosity of air ($m^2\ s^{-1}$) and D is hydraulic diameter perpendicular to the inflow direction of a room expressed in terms of the room height H and width B by:

$$D = \frac{2BH}{B+H} \tag{5}$$

The hypothetical mean air speed in a room v_m ($m\ s^{-1}$) is defined by [10, 11]:

$$V_m = \frac{Q}{BH} \tag{6}$$

Values of v_m would be very closed to u_{room} for smaller rooms, but differences are expected in bigger ventilated spaces.

A good parameter found to be useful is the modified jet momentum number J^* [8]. This was derived using the concept of the jet momentum number J proposed by

Table 1
Summary information of the investigating sites and measuring parameters

Station	A	B	C	D	E	F	G
Dimension:							
Length: L/m	79	47.5	56.3	49	46.1	67.5	17.4
Width: W/m	16	21.5	23	28.6	18.5	15.65	10.7
Height: H/m	7.18	7	4.25	3.58	4.02–7.8	5.58	2.9
No. of measurement positions	48	43	50	45	41	50	62
Ventilation system:							
Mean inlet velocity U_{di}/m s^{-1}	1.01*(1.922)	2.62	1.32	1.7	1.59	4.53	1.58
Mean inlet temperature T_{di}/°C	21	9	22	17	17	15	21
Mean room temperature T_{room}/°C	21.7	10.7	22.7	18.2	17.3	15.2	22.6
Hypothetical mean air velocity calculated by eqn (6) v_m/m s^{-1}	0.0082	0.0245	0.0132	0.0100	0.0372	0.0897	0.0024
Supply flow rate Q/m^3 s^{-1}	4.678	8.157	17.09	14.06	6.882	23.67	0.455
Air exchange rate (by inlet) ACH/h^{-1}	1.86	4.12	11.19	10.07	5.24	22.04	3.03
Ventilation rate VR/d m^3 s^{-1} m^{-2}	3.70	8.01	13.21	10.02	8.08	23.94	2.45
Modified jet momentum number $J^*/\times 10^{-5}$	13	45	42	49	33	280	14
Reynolds number $Re/\times 10^5$	1.9	3	3.3	5.5	0.8	1.7	0.96
Mean diffuser spacing S_d/m	15.5	13	6.3	7.4	18.6	13.15	10.7
Flow number X_1	0.0334	0.1410	0.1379	0.1388	0.0547	0.2175	0.0803
Flow number X_2	1.09	1.24	6.99	2.15	1.38	0.22	0.91
u_{mean}/m s^{-1}	0.207	0.346	0.146	0.222	0.157	0.310	0.103
u_{max}/m s^{-1}	0.37	0.66	0.33	0.49	0.25	0.58	0.33
u_{min}/m s^{-1}	0.06	0.19	0.07	0.12	0.08	0.14	0.05
u_{25}/m s^{-1}	0.158	0.28	0.113	0.17	0.12	0.22	0.075
u_{50} (or u_{med})/m s^{-1}	0.2	0.32	0.14	0.19	0.17	0.275	0.09
u_{75}/m s^{-1}	0.253	0.415	0.17	0.27	0.18	0.38	0.12
$u_R = u_{75} - u_{25}$/m s^{-1}	0.095	0.135	0.058	0.1	0.06	0.16	0.045
PD_{mean}/%	12.14	34.84	8.09	16.43	12.82	26.08	5.40
PD_{max}/%	20.10	56.70	15.66	30.46	6.02	14.86	3.63
PD_{min}/%	2.17	21.32	2.96	9.27	19.41	42.69	17.47
PD_{25}/%	9.84	29.25	6.60	13.31	10.15	19.60	3.63
PD_{50}/%	11.87	33.22	8.11	15.20	13.69	25.64	4.95
PD_{75}/%	14.37	40.99	9.75	19.41	14.92	31.94	7.18
$PD_R = PD_{75} - PD_{25}$/%	4.53	11.74	3.15	6.10	4.77	12.34	3.55

* Including an inlet at very high level.

Barber et al. [10, 11] and Ogilvie and Barber [12] to be used as a design criterion for air diffuser system in correlating with the air speeds at the occupied zone. The jet momentum number J is a measure of the energy contained in the supply air jet. It was defined by the supply air jet momentum divided by the room volume V_{room} in order to incorporate enclosure size; and by the constant of acceleration due to gravity (9.81 m s^{-1}) for dimensionless number:

$$J = \frac{Qu_{di}}{gV_{room}} \tag{7}$$

where u_{di} (m s^{-1}) is the average air face velocity over the diffusers.

The idea was confirmed experimentally by Ogilvie and Barber [12]. As reviewed by Li et al. [13], a jet momentum number greater than 7.5×10^{-4} was needed for an incoming air jet attended to the ceiling to distribute air at the occupied zone. This was further developed and calculated by including the height of diffuser above the ground level:

$$J^* = \frac{Qu_{di}}{gA_{room}h} \tag{8}$$

where h is the height of the centre line of the supply air jet from the floor level (m). Values of the two macroscopic numbers Re and J^* in the seven railway stations are shown in Table 1.

3. Mean air speed at 1.45 m above floor level

The mean air speeds at 1.45 m above floor level of the seven waiting halls were measured. The room mean air speed u_{mean} is the average value of the measured mean air speeds u at the different positions at 1.45 m above floor level. The room mean air speed u_{mean} was used to evaluate the Reynolds number defined in eqn (4). Typical mean air speed contour curves in stations E are shown in Fig. 1. Values of the mean air speeds at different positions of each station are different, varying from 0.1–0.3 m s^{-1}. Therefore, using it as a lumped parameter is not good enough to determine the thermal comfort in such halls. Also, values of the mean air speed vary considerably from one site to another. There were complaints on 'draughtiness' in waiting halls with high mean air speeds, and the feelings of 'lack of air movement' in waiting halls where the mean air speeds are low.

Values of the mean air speed are analyzed statistically by observing their measured frequency distributions at each station. Maximum value u_{max}, minimum value u_{min} and median value u_{50} for each station are calculated and shown in Table 1. The mean air speed u_{mean} is the average value of those mean air speeds u measured over the time interval of 3 min at different locations. The u_{max} is the maximum value of u; and u_{min} is the minimum value of u, among those measuring positions. The u_{50} is the value in the middle of the set of measured air speed u when arranged in order.

The cumulative frequency distribution curves for the air speeds are calculated. Values of the air speeds u_{25}, u_{50} and u_{75} corresponding to 25, 50 and 75% of results observed less than that air speed are shown in Table 1. The u_{25}, u_{50}, and u_{75} represent first quartile (25th percentile), median value (50th percentile) and third quartile (75th percentile) of the measured data set for u. The range of u_R is calculated from the differences of u_{75} and u_{25} is also shown in Table 1.

4. Predicted percentage of discomfort (*PD*)

The human response to the thermal environment induced by draught can be predicted by the predicted percentage of discomfort (*PD*) at a point from the mean air speed u, turbulence intensity Tu and air temperature Ta at that point as proposed by Fanger et al. [9, 14]:

$$PD = (3.143 + 0.369uTu)(34 - Ta)(u - 0.05)^{0.6223} \quad (9)$$

This expression was modified by Chow and Fung [15] that elevated air speed might be more comfortable to local people when temperature is higher than 28°C. A factor known as percentage of people feeling less comfortable (*PLC*) was proposed for that. However, the air temperature was lower than 28°C during the field measurement and so the parameter *PD* was used.

The values of *PD* were calculated from the measured u, Tu and Ta at the occupied zone at the same locations

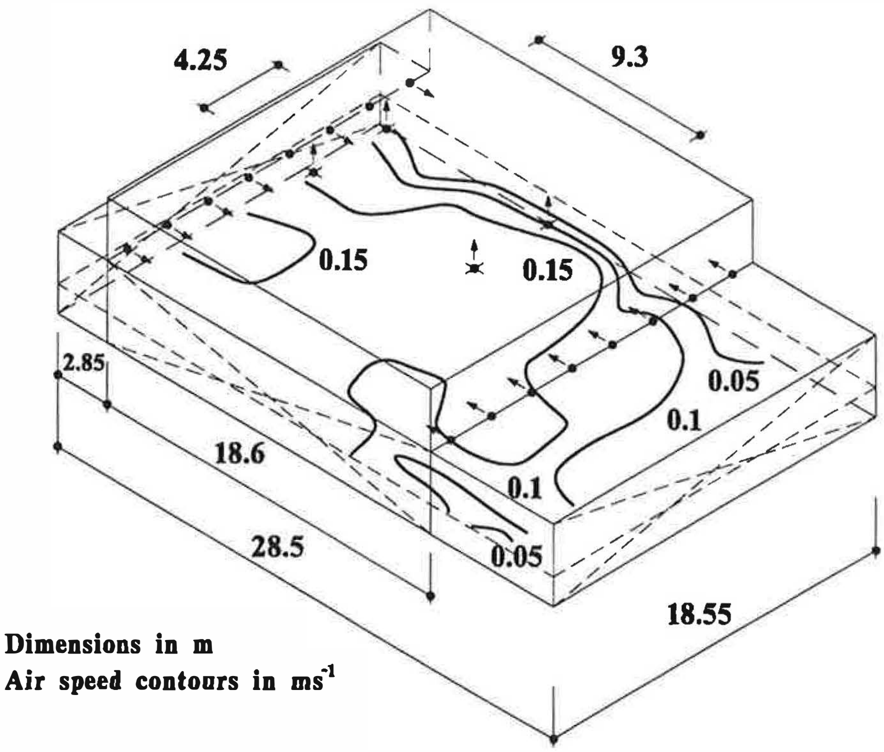

Fig. 1. Typical mean air speed contours in station E.

as those for measuring air speeds. Results were analyzed statistically to get the mean PD_{mean}, minimum PD_{min}, maximum PD_{max}, first quartile PD_{25}, medium value PD_{50} and third quartile PD_{75} as shown in Table 1. The range of PD denoted by PD_R is calculated from $PD_{75}-PD_{25}$.

5. Correlation of air speeds with macroscopic flow parameters

The values u_{25}, u_{50} and u_{75} are plotted against the macroscopic flow numbers including the air exchange rate ACH, the ventilation rate VR, the Reynolds number Re and the modified jet momentum number J^* from Figs 2–5.

The measured air speeds and the macroscopic numbers were analyzed by Regression analysis [16]. The linear correlation between a pair of experimental data (F, G) is:

$$G = \alpha \cdot F \tag{10}$$

If there are N pairs of experimental data (F_i, G_i), $i = 1, 2, 3, \ldots, N$, the method of least square fitting is commonly employed to derive the correlation relation. The deviation E_{ri} from the correlation relation for each pair of data is:

$$E_n = G_i - \alpha \cdot F_i \tag{11}$$

The constant α is determined by differenting the sum of errors squared $\Sigma_i E_{ri}^2$ with respect to α and setting the result to zero:

$$\frac{\mathrm{d}\left(\sum_i E_{ri}^2\right)}{\mathrm{d}\alpha} = 0 \tag{12}$$

Expression for α is:

$$\alpha = \frac{N\left(\sum_i F_i \cdot G_i\right) - \left(\sum_i F_i\right)\left(\sum_i G_i\right)}{N\left(\sum_i F_i^2\right) - \left(\sum_i F_i\right)^2} \tag{13}$$

The correlation coefficient $\mathfrak{R}$ expressed in terms of the sample variances υ_{FF} and υ_{GG}; and sample covariance υ_{FG} of F_i and G_i is used to assess the correlation relationship:

$$\mathfrak{R} = \frac{\upsilon_{FG}}{(\upsilon_{FF} \cdot \upsilon_{GG})^{1/2}} \tag{14}$$

with

$$\upsilon_{FF} = \frac{\sum_i (F_i - \bar{F})^2}{(N-1)} = \frac{\sum_i F_i^2 - N \cdot \bar{F}^2}{(N-1)} \tag{15}$$

$$\upsilon_{GG} = \frac{\sum_i (G_i - \bar{G})^2}{(N-1)} = \frac{\sum_i G_i^2 - N \cdot \bar{G}^2}{(N-1)} \tag{16}$$

and

$$\upsilon_{FG} = \frac{\sum_i F_i \cdot G_i - N \cdot \bar{F} \cdot \bar{G}}{(N-1)} \tag{17}$$

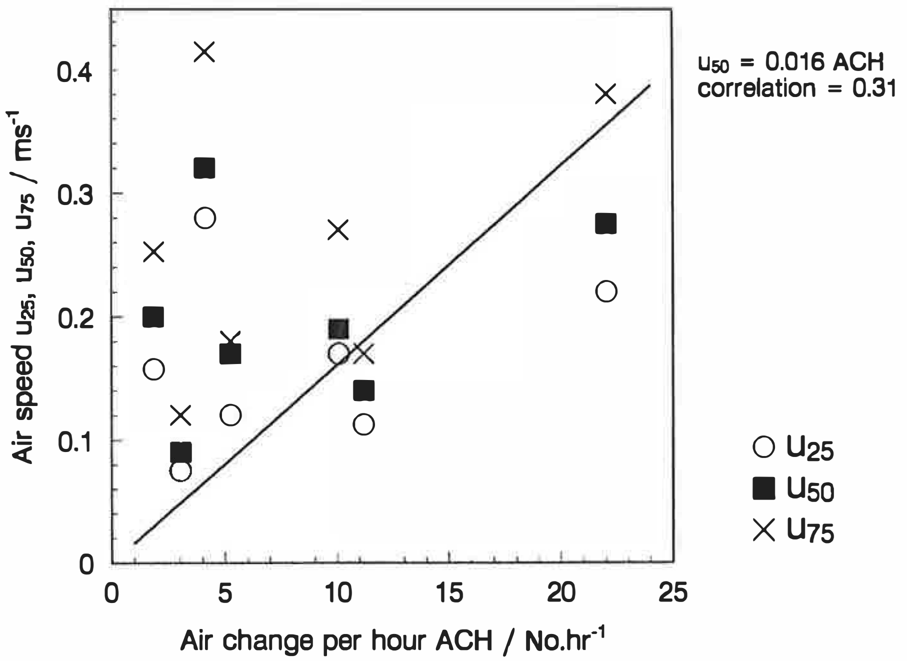

Fig. 2. Air speed u_{25}, u_{50}, u_{75} against air exchange rate.

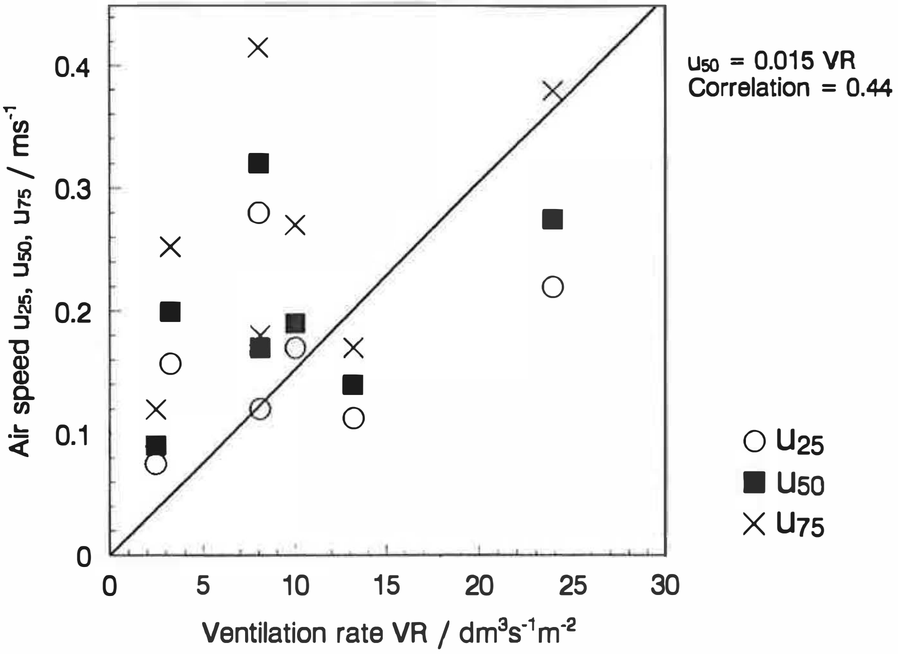

Fig. 3. Air speed u_{25}, u_{50}, u_{75} against ventilation rate.

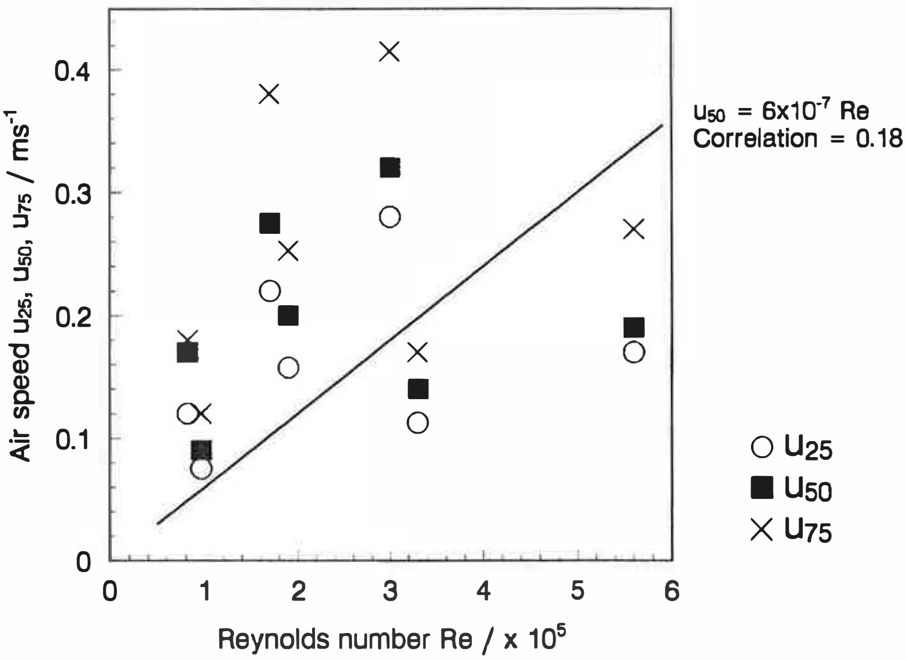

Fig. 4. Air speed u_{25}, u_{50}, u_{75} against Reynolds number.

where $\bar{F}$ and $\bar{G}$ and are the sample means of F_i and G_i and given by:

$$\bar{F} = \frac{\sum_i F_i}{N} \tag{18}$$

$$\bar{G} = \frac{\sum_i G_i}{N} \tag{19}$$

Weak correlation relationship is resulted for $\Re$ approaches zero. The correlation relationship is strong for $\Re$ tends to 1.

Macroscopic numbers (e.g. ACH and VR) are common design criteria for a ventilation system. Operation engineers are interested to know the condition in the occupied zone under different operating conditions of the system and so correlation relationships between the measured air speeds and the macroscopic numbers are found. Not

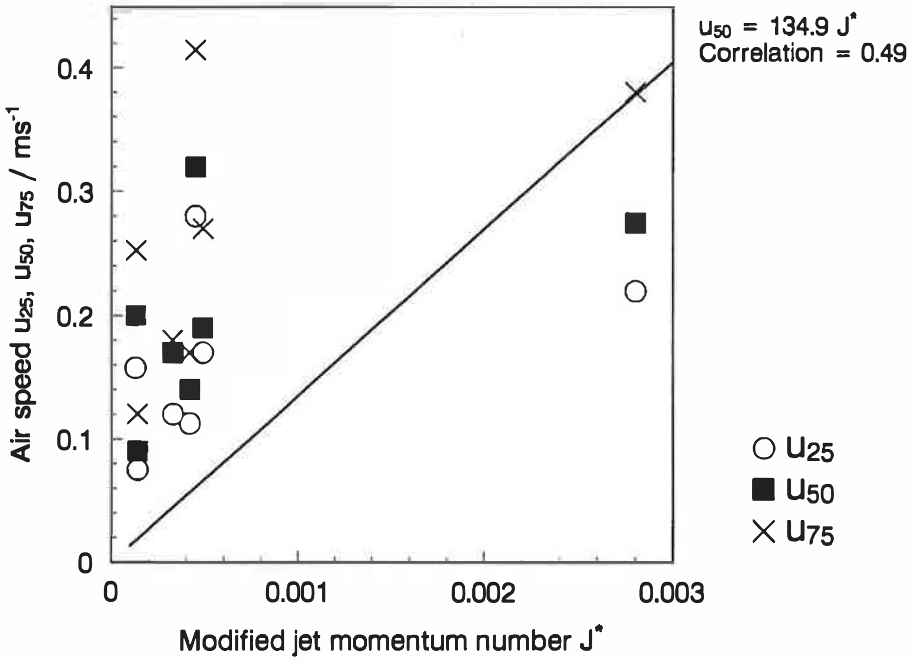

Fig. 5. Air speed u_{25}, u_{50}, u_{75} against modified jet momentum number.

very good linear correlation relationships are observed between those macroscopic numbers and the air speeds. Examples for fitting u_{50} with each of the flow numbers *ACH*, *VR* and *Re* by a straight line are shown in Table 2 together with the correlation coefficients.

The air exchange rate *ACH* commonly used in the industry is not a good parameter for specifying the air quality in the enclosure. This is very obvious in large spaces with incomplete mixing due to improper air distribution system design with the air diffusers. Without a good air distribution system, simply increasing the air exchange rate may not improve the air quality in the occupied zone. This is demonstrated clearly in this study.

There is a better correlation between the values for u_{50} at the occupied zone with the modified jet momentum number which was adjusted to include the height of the supply air jet. A linear relationship between the modified jet momentum number J^* and the room mean air speed u_{50} in the occupied zone of correlation coefficient 0.49 was derived as:

Table 2
Linear correlation relations between u_{50} and flow numbers

Linear equation	Correlation coefficient
$u_{50} = 0.161ACH$	0.31
$u_{50} = 0.015VR$	0.44
$u_{50} = 6\times10^{-7}Re$	0.18
$PD_{50} = 0.014ACH$	0.30
$PD_{50} = 0.013VR$	0.44
$PD_{50} = 4.95\times10^{-7}Re$	0.16

$$u_{50} = 134.9J^* \quad (20)$$

Correlation relationships between PD_{50} and the macroscopic numbers *ACH*, *VR* and *Re* were found and shown in Table 2. The correlation coefficients were very low. The relation with J^* is better as shown in Fig. 6 with a correlation coefficient of 0.49:

$$PD_{50} = 121.3J^* \quad (21)$$

6. The new flow numbers X_1 and X_2

The relationship relating u_{50} and J^* given by eqn (20) is still not promising as the separation distances S_d of the diffusers are not included. A new flow number X_1 defined by considering the relative value of the range R to be distributed by a diffuser and the spacing S_d as shown in Fig. 7 is proposed. The range R would be different for air discharged by ceiling diffusers and linear diffusers; and depends on the temperature of the air discharged. For air discharging at a temperature very close to the ambient, the range can be approximated by the equation for a free particle trajectory under gravity:

$$R \sim u_{di}\sqrt{\frac{2h}{g}} \quad (22)$$

The new flow number X_1 can be defined by the ratio of R to S_d, leaving all the other parameters to be constant:

$$X_1 = \frac{u_{di}}{S_d}\sqrt{\frac{h}{g}} \quad (23)$$

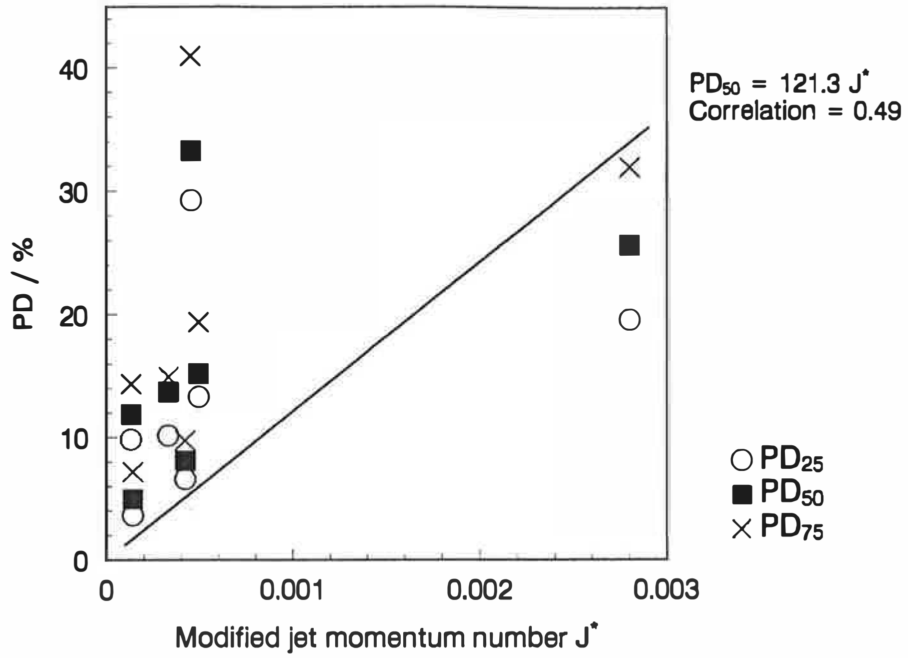

Fig. 6. Percentage of discomfort PD_{25}, PD_{50}, PD_{75} against modified jet momentum number.

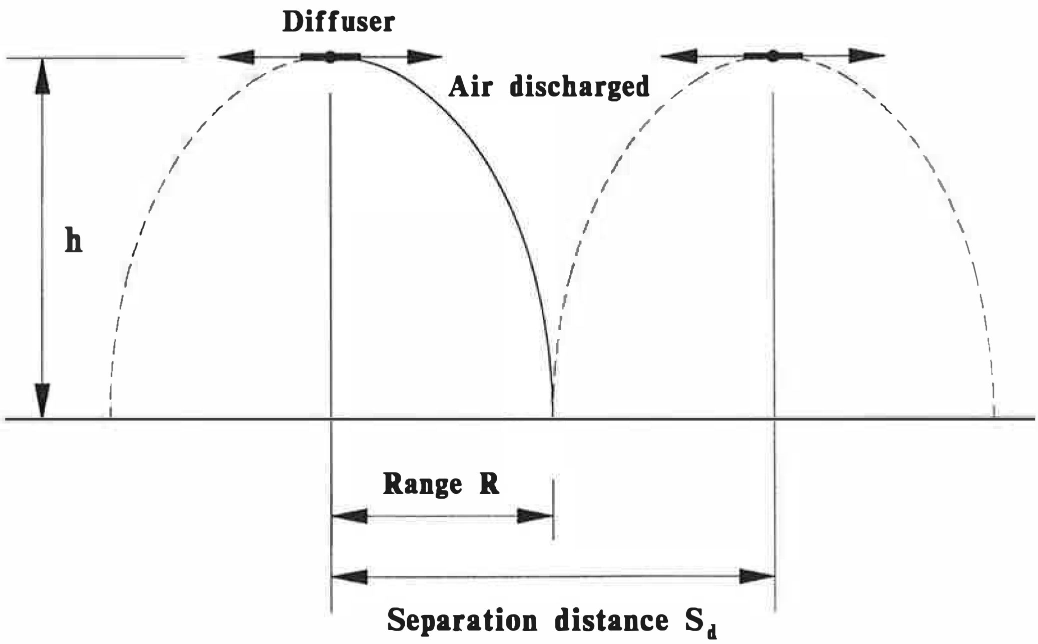

Fig. 7. Range of diffuser.

It is expected that larger the X_1 number, the shorter the value of S_d with respect to the range R and so a higher value of u_{50} will be the result. The values of S_d were calculated from the average of the diffuser spacings and shown together with X_1 in Table 1.

Values of u_{50} are plotted against X_1 in Fig. 8 and the following line with correlation coefficient 0.50 was fitted:

$$u_{50} = 1.5X_1 \tag{24}$$

Another flow number X_2 is also proposed by considering

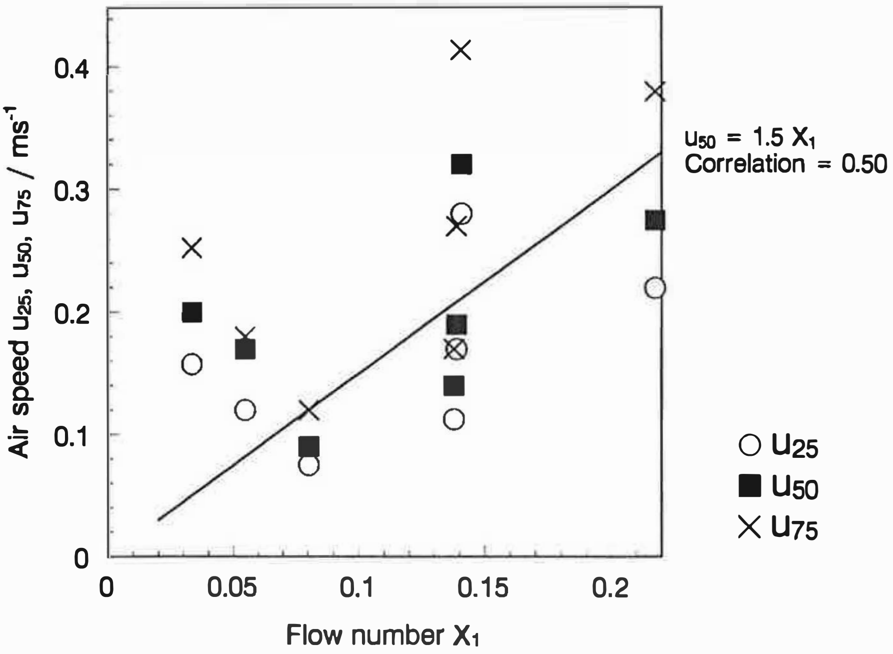

Fig. 8. Air speed u_{25}, u_{50}, u_{75} against flow number X_1.

the trajectory equation reported in the literature [13, 17]. An equation relating the horizontal distance z from the jet to the vertical distance x was found:

$$z \sim \frac{x^3}{u_{\mathrm{di}}^2} \tag{25}$$

The flow number X_2 can be derived by taking x to be the height h of the diffuser above the ground level:

$$X_2 \sim \frac{h^3}{S_{\mathrm{d}} u_{\mathrm{di}}^2} \tag{26}$$

The values of u_{50} are plotted with X_2 in Fig. 9 and the following equation with a correlation coefficient of 0.36 was found:

$$u_{50} = 0.24X_2 \tag{27}$$

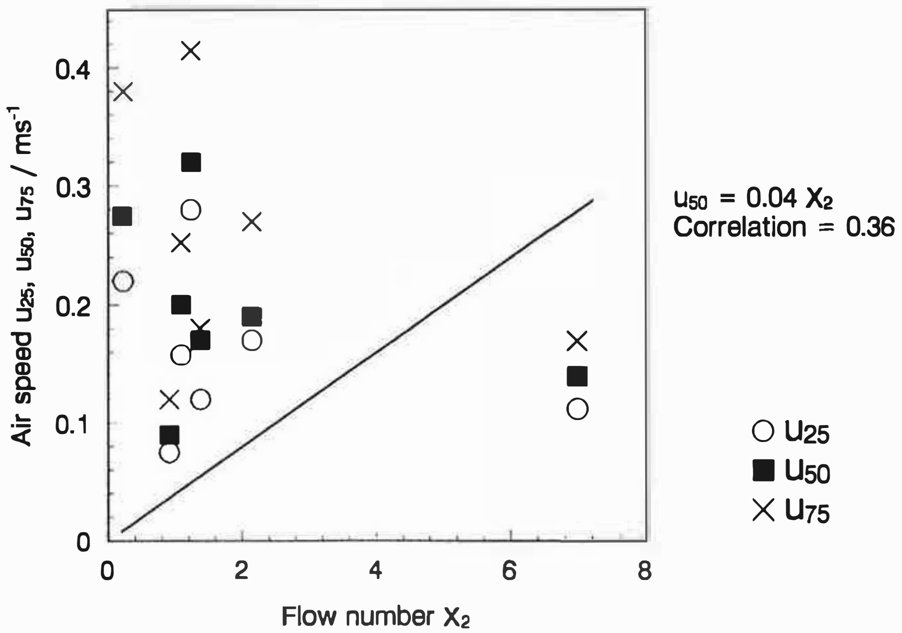

Fig. 9. Air speed u_{25}, u_{50}, u_{75} against flow number X_2.

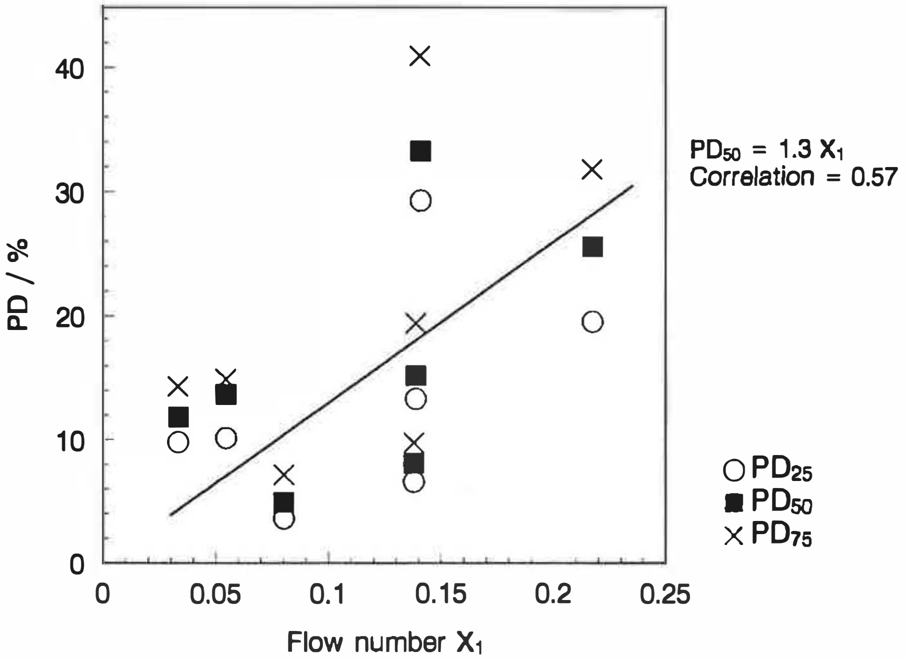

Fig. 10. Percentage of discomfort PD_{25}, PD_{50}, PD_5 against flow number X_1.

It can be seen that the flow number X_2 is not as good as X_1 in specifying the air speed at the occupied zone and it is even worse than the modified jet momentum number J^*.

Further, correlations between PD_{50} with X_1 and X_2 are found with correlation coefficients 0.57 and 0.39, respectively:

$$PD_{50} = 1.3X_1 \quad (28)$$

$$PD_{50} = 0.029X_2 \quad (29)$$

Again, the flow number X_1 gives a better correlation as shown in Fig. 10.

7. Conclusions

Data on the air speeds measured [7, 8] in the occupied zone of waiting halls in seven large railway stations with mechanical ventilation were further analyzed and reported. Those values were induced by the ventilation system under the normal modes of operation. The measured air speed and percentage of discomfort (PD) at the occupied zone of different positions in each hall were analyzed statistically to get the maximum, minimum, medium, 25th percentile, 50th and 70th percentile values.

Four macroscopic flow numbers commonly used in the literature [4–13] were calculated to check for correlation relationship with the measured air speeds and percentage of discomfort. Those numbers were the air exchange rate, the ventilation rate, the Reynolds number and the modified jet momentum number. It is found that macroscopic numbers commonly used in ventilation design such as air exchange rate and ventilation rate are good enough in specifying the performance of the ventilation system for large spaces. It is found that both the mean air speeds and the percentage of discomfort give a better correlation with the modified jet momentum number for large ventilated spaces.

Two more flow numbers X_1 and X_2 were defined by considering the range to be covered by each diffuser. The flow number X_1 was defined by taking the supply air jet trajectory similar to the free particle trajectory and the flow number X_2 was defined by considering empirical expressions on the air trajectory. It is found that the first flow number X_1 gives a better correlation with the mean air speeds and the percentage of discomfort.

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