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Technical Note

Summary Macroscopic flow numbers relating to the jet momentum of air diffusion terminal devices are studied in this paper. Diffuser jet momentum, jet momentum number and jet momentum ratio are reviewed in the literature. New expressions for jet momentum ratios and jet volume numbers are proposed for specifying the mean room air speed in mechanically ventilated enclosures. The proposal is validated against experimental data from seven sites under fifteen operating flow conditions. Two macroscopic flow numbers correlate with the measured mean air speed in the room.

Air diffusion terminal devices: Macroscopic numbers describing jet momentum

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List of symbols

J_i Diffuser jet momentum defined by Kaul *et al.*[12] as shown in equation 1 (kg m s^{-2})
ρ Air density (kg m^{-3})
Q_i Volume flow rate (m^3 s^{-1})
u_i Average velocity at the diffuser inlet (m s^{-1})
u_{room} Room mean air speed (m s^{-1})
u_x Centreline velocity (m s^{-1})
J_{mi} Diffuser jet momentum volume ratio defined by Kaul *et al.*[12] as shown in equation 2, (kg s^{-2} m^{-2})
J_m Jet momentum number proposed by Barber *et al.*[8] as shown in equation 3
V Volume (m^3)
g Gravitational constant (= 9.8 m s^{-2})
H Height (m)
L Length (m)
A Area (m^2)
h Height above floor level (m)
x Distance (m)
K, K' Proportionality constants
J^*_m Modified jet momentum number proposed by Chow *et al.*[10] as shown in equation 8
R_M Jet momentum ratio proposed by Adre and Albright[11] as shown in equation 4 (m^{2}s^{-2})
R_{M1}, R_{M2}, R_{M3} Jet momentum ratios (m^2 s^{-2})
Y_1, Y_2 Jet volume numbers (m^{-2})
D Distance (m)

Subscripts

i Of inlet
room Of room
x Of distance away from inlet
io Between inlet and outlet
ip Between inlet and occupied zone
op Between outlet and occupied zone

1 Introduction

Mechanical ventilating and air-conditioning (MVAC) systems for buildings are designed to maintain an acceptable thermal environment in the occupied zone. Parameters[1–3] affecting thermal comfort such as air velocity, ambient temperature and air humidity are controlled by the MVAC system. Therefore typical design parameters for indoor spaces with MVAC systems are the dry-bulb temperature, the relative humidity and the room mean air speed[2,4,5]. Local air speeds play an important role in thermal comfort[1] and air speed limits are specified in the principal design guides[2,4,5]. However, only temperature and humidity in the occupied zone are controlled in most of the MVAC systems, through placing sensors in selected locations. It is not common to control local air speed automatically by installing sensors in the system.

MVAC system designs are based on macroscopic flow numbers such as the of air change rate, the ventilation rate and air diffusion performance index. The air diffusion system is a key component in MVAC, affecting both the local air speeds and temperatures in the occupied zone. Understanding indoor air movement is very important in evaluating the performance of MVAC systems and determining the thermal comfort in a building[6]. Discomfort due to 'draught' or 'unwanted local cooling of the human body caused by air movement' have been reported in spaces with poorly designed air diffusion systems. The indoor air flow pattern is affected by the selection[5] and location of the air diffusion terminal devices[7]. Experimental studies on the correlation between local air speeds and jet momentum numbers have been reported[8–10], but understanding of the correlation relationships among the macroscopic flow numbers specifying air diffusion terminal device, the resulting flow field, and the perception of occupants on the environment are still inadequate.

Although air speed is very important in evaluating thermal comfort, it is not a control parameter in most MVAC systems. The local air speeds in the occupied zone depend on the design of the air diffusion system. It is difficult to specify the local comfort conditions in the occupied zone at the design stage because the local air speed cannot be determined easily. Relating the macroscopic numbers to the local conditions would provide a solution. Macroscopic flow numbers are proposed in this paper as design parameters for the practical design of MVAC systems.

2 Jet momentum number

As reviewed by Adre and Albright[11], the diffuser jet momentum J_i defined as the mass flow rate multiplied by the average velocity ui at the diffuser inlet (in m s^{-1}) was proposed by Kaul *et al.*[12] as a criterion for determining whether the jets in a ventilation system would give the desired air distribution mixing patterns in the enclosures. It is given in terms of the volume flow rate Q_i (in m^{3}s^{-1}) and the air density ρ by:

$$J_i = \rho Q_i u_i \quad (1)$$

Another number was proposed by Kaul *et al.*[12]; the diffuser jet momentum J_i is divided by the enclosure volume V_{room} so as to include the dimensions of the enclosure. The number J_{mi} is given by:

$$J_{mi} = J_i/V_{room} \quad (2)$$

For rooms with a ratio of width to height less than 6, a minimum J_{mi} of 10×10^{-3} kg m^{-2} s^{-2} was suggested to ensure stable rotary flow under isothermal conditions.

The concept was extended by defining a dimensionless jet momentum number J_m as:

$$J_m = J_{mi}/\rho g \quad (3)$$

A threshold value of J_m was suggested as 7.5×10^{-4} to achieve suitable airflow patterns. Further studies[9] on this number show that the jet momentum number may be considered as an index of air velocity at 0.3 m above floor level.

The similarity criterion was studied experimentally for two-dimensional wall jet airflow patterns in confined spaces[11]. A jet momentum ratio R_M was proposed as the appropriate similarity criterion as the dimensions of the enclosure are included. This was obtained by dividing the inlet air jet momentum by the streamwise length expressed as the sum of the enclosure height H_{room} and the enclosure length L_{room}. Rewriting Q_i as $u_i A_i$, where A_i is the inlet area of the diffuser, R_M is expressed in terms of the height of the diffuser h_i above ground level as:

$$R_M = u_i^2 h_i/(L_{room} + H_{room}) \quad (4)$$

The inlet jet momentum is a key factor in determining the centreline velocity u_x in zone 3 of an air jet[5] at a distance x away from the inlet:

$$u_x/u_i = KA_i^{1/2}/x \quad (5)$$

In equation 5 K is a proportionality constant. Rearranging equation 5, u_x can be expressed in terms of J_m and another constant K' as:

$$u_x = K' J_m^{0.5}/x \quad (6)$$

Using experimental data from the literature, a correlation relation between the air speed at 0.3 m above floor level (denoted by $u_{0.3}$) and J_m with a correlation coefficient r^2 of 0.85 was found[9]:

$$u_{0.3} = 4.8 J_m^{0.359} \quad (7)$$

The jet momentum number J_m was further modified[10] for wall-mounted diffusers to obtain a modified jet momentum number J_m^* by taking into account the height of air diffuser above the floor level h_i:

$$J_m^* = Q_i u_i/g A_{room} h_i \quad (8)$$

Correlation between J_m^* and the mean air speed in the occupied zone of the enclosure was studied[13]. The correlation coefficients were not high, although the jet momentum was believed to be a good flow parameter for specifying the performance of the ventilation system in terms of the room air speed. Further invesitgation is necessary and is reported here.

3 New macroscopic flow numbers

Macroscopic flow numbers related to the jet momentum of the air diffusion terminal devices has been investigated further. Correlation of these numbers with the room mean air speed u_{room} was studied. Different values of streamwise length derived by considering the distance between the inlet and outlet D_{io}; the distance between the inlet and occupied zone D_{ip}; and the distance between the outlet and occupied zone D_{op} were considered; all are shown in Figure 1. Three expressions for the jet momentum ratios R_{M1}, R_{M2} and R_{M3} are proposed:

$$R_{M1} = u_i^2 A_i/D_{io} \quad (9)$$

$$R_{M2} = u_i^2 A_i/(D_{ip} + D_{op}) \quad (10)$$

$$R_{M3} = u_i^2 A_i/(D_{ip} + D_{op})^2 \quad (11)$$

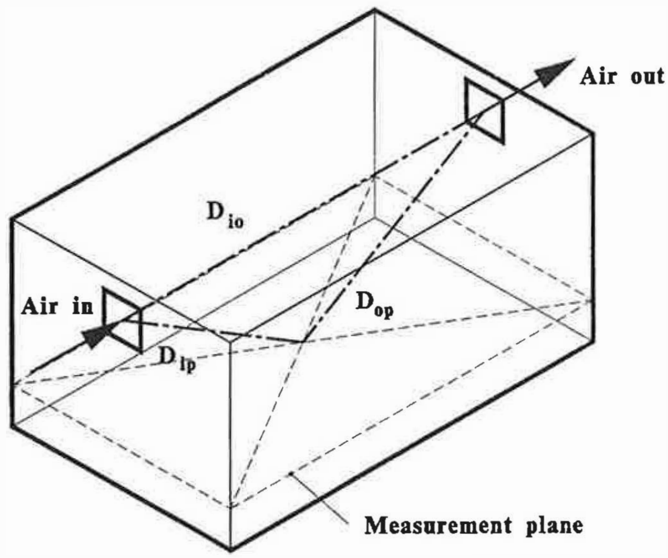

Figure 1 Geometry

Two more expressions for the jet volume numbers Y_1 and Y_2 calculated from J_m (Reference 8) and J_m^* (Reference 10) by including the geometry of the room with respect to the diffuser are proposed as follows:

$$Y_1 = J_m/(D_{ip} + D_{op})^2 \quad (12)$$

$$Y_2 = J_m^*/(D_{ip} + D_{op})^2 \quad (13)$$

The jet momentum ratios R_{M1}, R_{M2} and R_{M3} and the new jet volume numbers Y_1 and Y_2 are proposed for use as an index for specifying the room mean air speed due to the diffuser.

4 Review of experimental data

The experimental data from pervious studies on air flow chambers[13,14] and railway waiting halls[10] were used to assess the proposed flow numbers. The measured air speeds at different locations in seven mechanically ventilated spaces were studied. The room mean air speed was calculated for each case. The experiments are described briefly below.

Indoor air flow characteristics induced by a linear diffuser[14] (and a high-sidewall grille[13] in an air-conditioned environmental chamber were studied experimentally. Nine flow conditions, four with linear diffuser, two with a high sidewall grille and three with a high sidewall opening (without diffuser) were studied. Evaluation of the thermal comfort using air diffusion performance index (ADPI) and percentage dissatisfied (PD) was reported in References 13 and 14. Macroscopic numbers describing indoor air flow including the Archimedes number, the Reynolds number and the jet momentum number were measured. Variations of those thermal comfort indices with different values of the macroscopic physical numbers for the air flow under isothermal conditions were discussed and empirical correlations derived.

Air speeds induced by mechanical ventilation at the occupied zone were studied[10] experimentally in seven railways stations in Hong Kong. Air speeds at different positions were measured and air speed contours and turbulence intensity were calculated. Macroscopic numbers describing air flow in the space including the Reynolds number and the jet momentum number were estimated and their potential uses discussed.

Experimental details are reported elsewhere[10,13,14] and are not repeated here. Results are summarised in Table 1. Sufficient information is given to the seven flow numbers given by equations 3, 8 and 9 to 13.

5 Discussion

Relationships of the room mean air speed u_{room} with the jet momentum ratios R_{M1}, R_{M2} and R_{M3} and the jet volume numbers Y_1 and Y_2 were derived by the method of least square fitting. The fitted linear and non-linear equations are given in Table 2.

The fitted equations are graded as 'Good', 'Fair', 'Poor' and 'Unphysical' according to the calculated correlation coefficients. The equations relating u_{room} with R_{M1} and R_{M2} for ceiling-mounted diffusers, and u_{room} with $\mathcal{J}_m$, $\mathcal{J}_m^*$, Y_1 and Y_2 for wall-mounted diffusers, did not give physical results because the values of u_{room} decreased as those numbers increased. The derived expressions were rejected even though the correlation coefficients were high for the fit of $\mathcal{J}_m$ and Y_1 to experimental data for wall-mounted diffusers.

The jet volume number Y_1 is a good macroscopic flow number for relating the room mean air speed u_{room} to the jet momentum of ceiling-mounted diffusers. The correlation coefficient was 0.73 for the linear equation and 0.85 for the nonlinear equation. The correlation coefficients for the two fitted equations are higher than those derived for other flow numbers.

For wall-mounted diffusers, the jet momentum ratio R_{M2} is the best number for relating with the room mean air speed u_{room}. The correlation coefficient for the linear equation with u_{room} was 0.85 and 0.86 for the nonlinear equation.

The two recommended equations relating the macroscopic flow numbers Y_1 and R_{M2} with the room mean air speed u_{room} are plotted together with the measured data in Figures 2 and 3 respectively.

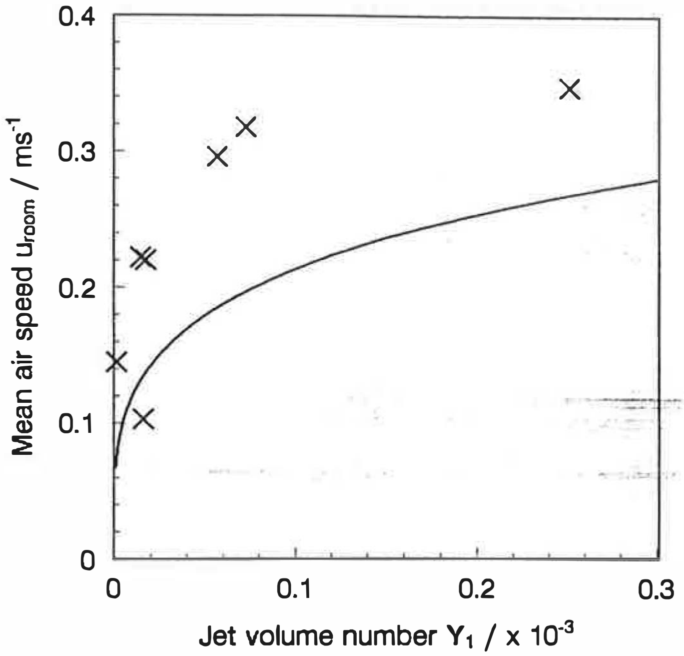

Figure 2 Correlation between mean air speed and jet volume number for ceiling-mounted diffuser (Curve: $U_{room} = 2.13Y_1^{0.25}$; correlation coefficient = 0.85)

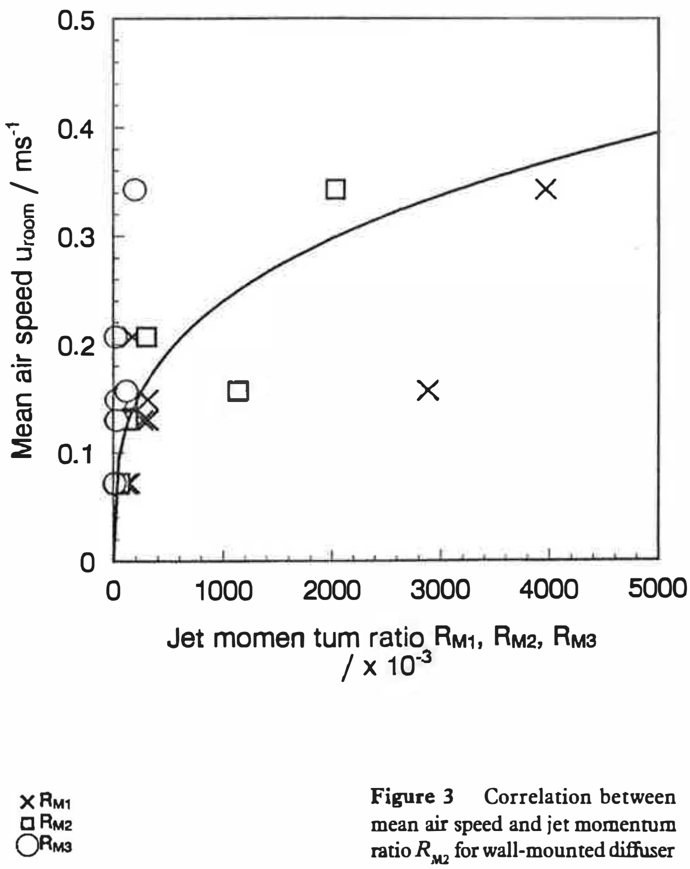

Figure 3 Correlation between mean air speed and jet momentum ratio R_{M2} for wall-mounted diffuser

6 Conclusions

Seven macroscopic flow numbers relating to the jet momentum of the air diffusion terminal devices were studied in this paper. Experimental data on air speeds measured at seven sites with mechanical ventilation under fifteen operating flow conditions were analysed. The volumes of the spaces varied from 22.4 m³ to 7 132 m³, and so the measured data can be viewed as typical examples for mechanically ventilated spaces in Hong Kong. By analysing previous experimental data measured earlier in the seven enclosures with mechanical ventilation, it is found that the jet volume number Y_1 can be used to specify the room mean air speed induced by ceiling-mounted diffusers and the jet momentum ratio R_{M2} for wall-mounted diffusers. Both numbers correlate well with the room mean air speed.

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Table 1 Summary of experimental results

Experiment	Room dimension					Room	Inlet conditions		Distances between			Jet numbers						
	Length L_{room} (m)	Width W_{room} (m)	Height H_{room} (m)	Area A_{room} (m^2)	Volume V_{room} (m^3)	mean air speed u_{room} (m s^{-1})	Mean velocity u_i (m s^{-1})	Face area A_i (m^2)	Inlet and outlet D_{io} (m)	Measuring plane and inlet D_{ip} (m)	Measuring plane and outlet D_{op} (m)	Momentum[8] $\mathcal{J}_m$ (×10^{-3})	Modified momentum[10] $\mathcal{J}_m$* (×10^{-3})	Momentum ratio R_{M1} (×10^{-3})	Momentum ratio R_{M2} (×10^{-3})	Momentum ratio R_{M3} (×10^{-3})	Volume number Y_1 (×10^{-6})	Volume number Y_2 (×10^{-6})
Air flow chamber with linear diffuser																		
Condition A	4.1	2.6	2.1	10.7	22.4	0.220	0.359	0.40	2.83	1.23	2.24	0.208		18.22	14.84	4.28	17.29	
Condition B	4.1	2.6	2.1	10.7	22.4	0.296	0.651	0.40	2.83	1.23	2.24	0.687		59.99	48.87	14.09	57.10	
Condition C	4.1	2.6	2.1	10.7	22.4	0.318	0.735	0.40	2.83	1.23	2.24	0.874		76.47	62.30	17.96	72.64	
Condition D	4.1	2.6	2.1	10.7	22.4	0.348	1.224	0.40	2.83	1.23	2.24	3.030		212.1	172.8	49.81	251.8	
Field survey on waiting halls with ceiling jets/diffusers																		
Site C	56.3	23.0	4.3	1294	2139	0.145	1.320	13.00	17.10	2.13	16.98	0.42		1323.9	1184.9	62.03	1.15	
Site D	49.0	28.6	3.6	1403	2158	0.222	1.700	8.30	5.09	2.13	5.51	0.844		4690.5	3120.7	408.30	14.45	
Site G	17.4	10.7	2.9	186	503	0.103	1.580	0.29	5.90	1.45	6.08	0.905		122.3	95.9	12.74	15.98	
Air flow chamber with wall jet																		
Condition A	4.1	2.6	2.1	10.7	22.4	0.149	3.01	0.06	1.83	2.19	1.22	5.32	5.67	311.1	128.7	29.01	270.4	288.2
Condition B	4.1	2.6	2.1	10.7	22.4	0.130	2.80	0.06	1.83	2.19	1.22	4.02	4.29	269.2	111.3	25.10	204.5	218.0
Condition C	4.1	2.6	2.1	10.7	22.4	0.076	1.84	0.06	1.83	2.19	1.22	2.05	2.19	116.3	48.08	10.84	104.2	111.1
Air flow chamber with wall-mounted air grille																		
Condition D	4.1	2.6	2.1	10.7	22.4	0.130	3.14	0.06	1.83	2.19	1.22	2.05	2.19	311.7	128.9	29.1	104.2	111.1
Condition E	4.1	2.6	2.1	10.7	22.4	0.073	2.12	0.06	1.83	2.19	1.22	0.965	1.03	142.1	58.77	13.25	49.02	52.25
Field survey on waiting halls with wall jets/diffusers																		
Site A	79	16	7.18	1264	6546	0.207	1.01	4.08	24.22	7.83	6.08	0.47	1.3	171.5	299.1	21.5	2.4	6.7
Site B	47.5	21.45	7	1019	7132	0.343	2.62	3.11	5.39	4.42	6.08	0.031	0.45	3965.3	2035.2	194.0	0.3	4.1
Site E	46.5	18.5	7.8	860	4730	0.157	1.59	4.32	3.79	2.57	7.08	0.24	0.33	2885.4	1132.8	117.5	2.6	3.6

Table 2 Summary of results

Diffuser	Linear expression for u_{room}	Correlation coefficient	Comment	Nonlinear expression for u_{room}	Correlation coefficient	Comment
Ceiling mounted	$158\mathcal{J}_m$	0.55	Fair	$1.35\mathcal{J}_m^{0.24}$	0.51	Poor
	$0.057R_{M1}$	0.17	Poor	$0.22R_{M1}^{-0.05}$	0.24	Unphysical
	$0.087R_{M2}$	0.22	Poor	$0.21R_{M2}^{-0.05}$	0.25	Unphysical
	$0.74R_{M3}$	0.07	Poor	$0.24R_{M3}^{0.004}$	0.01	Poor
	$1878Y_1$	0.73	Fair	$2.13Y_1^{0.25}$	0.85	Good
Wall mounted	$35.9\mathcal{J}_m$	0.38	Poor	$0.024\mathcal{J}_m^{-0.25}$	0.85	Good
	$37.9\mathcal{J}_m^*$	0.31	Poor	$0.026\mathcal{J}_m^{*-0.27}$	0.48	Unphysical
	$0.082R_{M1}$	0.76	Fair	$0.19R_{M1}^{0.27}$	0.73	Fair
	$0.18R_{M2}$	0.85	Good	$0.24R_{M2}^{0.31}$	0.86	Good
	$1.88R_{M3}$	0.83	Good	$0.57R_{M3}^{0.40}$	0.81	Good
	$644Y_1$	0.39	Poor	$0.019Y_1^{-0.19}$	0.87	Unphysical
	$637Y_2$	0.38	Poor	$0.017Y_2^{-0.21}$	0.67	Unphysical

Note: $\mathcal{J}_m$ and $\mathcal{J}_m^*$; Y_1 and Y_2 for ceiling inlets are identical.