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Experimental Studies on Air Diffusion of a Linear Diffuser and Associated Thermal Comfort Indices in an Air-conditioned Space

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Indoor air flow induced by a linear diffuser in an air-conditioned environmental chamber was studied experimentally. Macroscopic numbers describing indoor air flow such as the Archimedes number, the Reynolds number and the jet number were measured. Evaluation of the thermal comfort using the air diffusion performance index (ADPI) and the percentage dissatisfied (PD) was made. Comparison between those indices and the macroscopic numbers for the air flow are discussed.

1. INTRODUCTION

INDOOR air movement is very important in evaluating the ventilation design and determining the thermal comfort in a building. Complaints due to 'draft' or 'unwanted local cooling of the human body caused by air movement' would be reported in poorly ventilated spaces. Therefore, values of the air speed are also specified in the common design criteria and appear in thermal comfort indices such as the predicted mean vote (PMV), predicted percentage of dissatisfied (PPD) as in ISO7730 [1]. Air speed is used to determine the effective draft temperature (EDT), from which the air diffusion (distribution) performance index (ADPI) can be calculated. This parameter is useful in describing the diffusion performance of air for a diffuser in a ventilated space. On the other hand, macroscopic numbers are defined for describing the air flow and to some extent, they are useful in evaluating the design of air diffusion. Because there is a distribution of air velocity, using a single mean velocity is inadequate to determine the thermal comfort. Actually air flow induced by mechanical systems is turbulent and specifying the turbulence intensity is more important in describing air movement; e.g. Hanzawa *et al.* [2]. However, the airflow pattern in a building cannot be estimated easily. It depends on the design and performance of the supply air terminal devices (Whittle [3], Jackman [4]), geometry of the room, ventilation rate, partitions and obstructions. Studies with physical full-scale models would be very expensive and problems arise in scale models, particularly on conserving the Archimedes number and the Reynolds number (Chen *et al.* [5]). The objective of the paper is to study the performance of linear diffusers which it is (e.g. Hart and In-Hout [6]) believed can satisfy building comfort needs. Experimental measurements on the air flow pattern and the turbulence intensity induced by a linear diffuser in an air-conditioned environmental chamber were performed. Macroscopic numbers defined for describing the flow such as the Archimedes number, the Reynolds number and the jet number are evaluated. Indices such as the effective draft temperature (EDT), air diffusion performance index (ADPI) and predicted percentage of dissatisfied (PPD) are also surveyed.

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2. MACROSCOPIC NUMBERS

The first macroscopic number to be evaluated is the Archimedes number Ar which is a ratio of the buoyancy to dynamic pressure exerted on a typical fluid element. This number would characterize the motion of nonviscous and nonisothermal fluid. It is given by:

$$\mathrm{Ar} = \frac{gl(\rho_1 - \rho_2)}{V^2 \rho_2} \tag{1}$$

where ρ_1 and ρ_2 are densities of separate fluid elements, V is the characteristic air speed and l is the characteristic dimension. Because the air temperatures T_1 and T_2 (corresponding to ρ_1 and ρ_2) are easier to measure, it is better to calculate Ar from the temperatures:

$$\mathrm{Ar} = \frac{gl(T_2 - T_1)}{V^2 T_1}. \tag{2}$$

The choice of the characteristic length and the characteristic velocity affects the values of the Archimedes number. The characteristic length is taken by Nielsen *et al.* [7] to be the height of diffuser and the characteristic velocity V is taken as the inlet velocity. Two other forms have been considered by Randall and Battams [8]. The first one is taking l to be the hydraulic diameter of the room D which is calculated from the width B and height H of the room (in m):

$$D = \frac{2BH}{B+H}. \quad (3)$$

The characteristic velocity V is calculated from the flow rate through the diffuser inlet f ($m^3 s^{-1}$):

$$V = \frac{f}{BH}. \quad (4)$$

The second form is taking l to be the inlet area of the vent divided by the hydraulic diameter D, i.e.

$$l = \frac{ab}{D} \quad (5)$$

where a and b are the height and width of the vent in m.

However, as pointed out by Spitler [9], the Archimedes number is used mainly for predicting the trajectory of the inlet jet. The path of a horizontally projected jet is shown by Mullejans [10] to be a function of the Archimedes number.

The second macroscopic number is the Reynolds number which characterizes the dynamic and viscous forces of fluid and gives an idea of the level of turbulence in the fluid motion. Following Randall and Battams [8], the Reynolds number Re for a confined space is:

$$\mathrm{Re} = \frac{VD}{\nu} \quad (6)$$

where ν is the kinematic viscosity of air in $m^2 s^{-1}$.

Since the air flow in the air-conditioned space is turbulent, the turbulence intensity has to be measured. From its value, an important thermal comfort index due to draft, known as the percentage dissatisfied (Fanger *et al.* [11]), can be calculated. The instantaneous air velocity $V(t)$ at time t is fluctuating and a mean air velocity U can be measured over a certain time interval from t_0 to $t_0+\Delta t$. The turbulence intensity Tu is defined as the root-mean-square (RMS) of the velocity fluctuation U' over this interval of time divided by this mean velocity:

$$Tu = \frac{\sqrt{U'^2}}{U} \quad (7)$$

where

$$U = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} V(t)\,\mathrm{d}t \quad (8)$$

$$U'^2 = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} (V')^2\,\mathrm{d}t. \quad (9)$$

Using the measured turbulence intensity, the percentage dissatisfied PD can be calculated:

$$\mathrm{PD} = (3.143+0.3696U\,Tu)(34-T_a)(U-0.05)^{0.6223}. \quad (10)$$

Here, T_a is air temperature, U is taken to be 0.05 m s^{-1} if its value is less than 0.05 m s^{-1} and the maximum value of PD is 100%. Empirical constants in the above equation are determined by Fanger *et al.* [11].

The effective draft temperature (EDT) was defined by Rydberg and Norback [12] and later modified by Koestel and Tuve [13] as:

$$\mathrm{EDT} = (T_x - T_r) - 8(v_x - 0.15) \quad (11)$$

where T_x is the local air stream dry-bulb temperature in °C; T_r is the mean room dry-bulb temperature in °C and v_x is the local air stream velocity in m s^{-1}.

The air diffusion (distribution) performance index (ADPI) (e.g. ASHRAE Handbook—*Fundamentals* [14]) is a percentage that is defined by the number of points measured in an occupied zone where EDT is within the set limit (> −1.7°C and < 1.1°C) over the total number of points f measured in the occupied zone:

$$\mathrm{ADPI} = \frac{P_r}{f} \quad (12)$$

where P_r is the number of samples with the EDT lying between 1.1°C and −1.7°C.

Another parameter known as the jet number J is proposed by Barber *et al.* [15] to be set as a design criterion for the air diffuser system. This is calculated from the total ventilation rate Q ($m^3 s^{-1}$), mean air diffuser velocity U_{dm} (m s^{-1}) and the volume of the room V_{Room} (m^3):

$$J = \frac{QU_{dm}}{gV_{Room}}. \quad (13)$$

3. EXPERIMENTAL STUDIES

Experimental measurements were carried out in an environmental chamber at the Department of Building Services Engineering, Hong Kong Polytechnic. The chamber is of length 4.1 m, width 2.6 m and height 2.1 m as shown in Fig. 1. Air speeds at different locations in the compartment are measured by hot-wire anemometer placed in fifteen to nineteen different positions as shown in Fig. 2. At each position, measurements were taken during a 3-minute period at four heights which are 0.1, 0.6, 1.1 and 1.7 m above the floor level. The air diffuser is of the shape shown in Fig. 1 and its outlet velocities were measured. Four different flow conditions labelled as A, B, C, D were set as summarized in Table 1. The temperatures T_1 and T_2 in equation (2) are the supply air temperature and ambient air temperature respectively. The boundary of the environmental chamber was well insulated so the wall temperature differences at the four different flow conditions were very small.

The hot-wire anemometer used in this study is a tungsten probe of diameter 5 μm and electrical resistance 15 Ω. It is calibrated in a reduced scale air tunnel to have a measuring range from 0 m s^{-1} to 1.4 m s^{-1} at 18°C to 25°C. The accuracy of the electronic anemometer is ±3%, i.e. about 0.03 m s^{-1} for 1 m s^{-1}. A set of cali-

Table 1. Summary information of the environmental chamber

Flow condition	Supply flow rate in $m^3 s^{-1}$	Air change, $m^3 hr^{-1}$	Number of measuring points	Number of data
A	0.294	45.13	60	43,200
B	0.4896	75.16	72	57,600
C	0.2604	39.97	60	43,200
D	0.1435	22.03	60	43,200

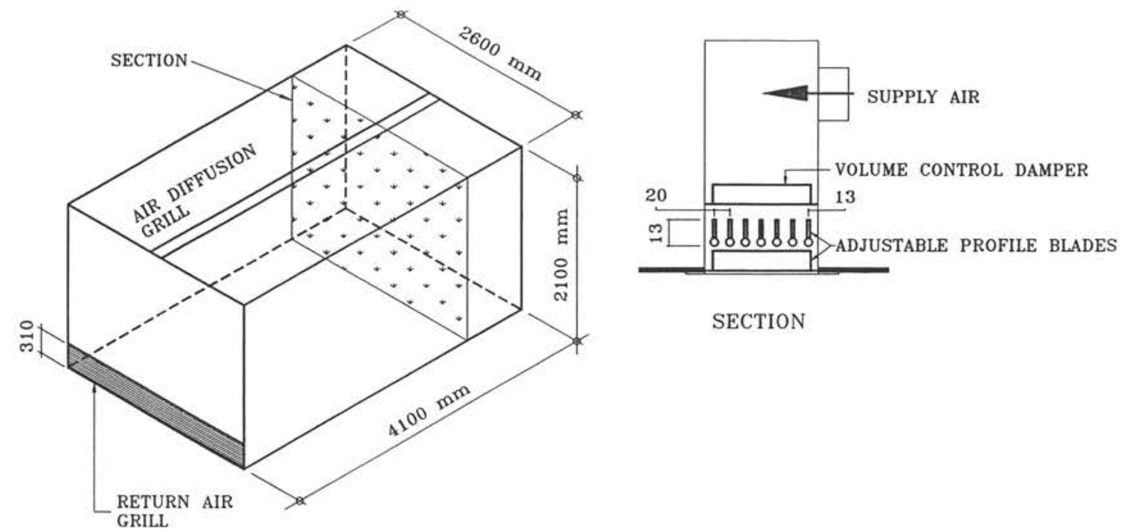

Fig. 1. Environmental chamber.

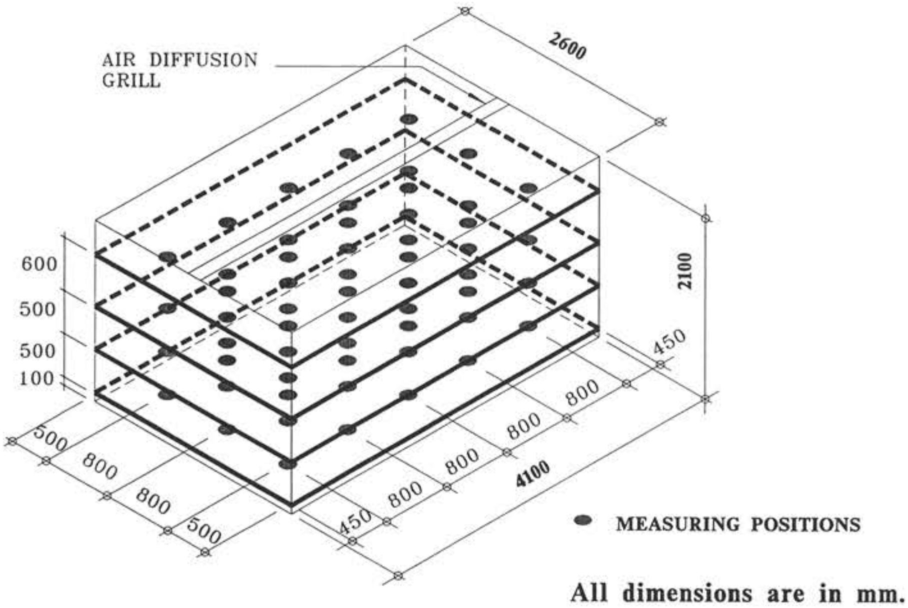

Fig. 2. Location of measuring points.

bration curves was obtained with 387 experimental points.

At each position of measurement, 710 instantaneous velocities were recorded. The air temperature and relative humidity were measured by K-type thermocouples and aspiration psychrometers respectively. The air temperature differences among the four levels were less than 2°C and values of the difference of the relative humidity were less than 7%.

4. RESULTS

The mean air speed contours in the environmental chamber for all the four conditions at ankle level (at 0.1 m above floor) and sitting head level (1.1 m above floor) are measured with typical flow conditions A and B and are shown in Figs 3 and 4. It is observed that the air speed at a certain position is generally higher if the air supply rate increases.

The measured EDT distribution and the ADPI in the environmental chamber at the four different air supply flow rates are shown in Fig. 5. It can be seen that the values of ADPI fluctuated as the supply flow rates increased because the EDT was higher than the set limits, and then fell within the limit when the supply air flow rate was increased to 0.294 $m^3\ s^{-1}$. The ADPI at the chamber decreased as the supply flow rate increased to 0.2604 $m^3\ s^{-1}$ so that EDT of some positions fell below the limit −1.7°C. As the supply flow rate increased to 0.294 $m^3\ s^{-1}$ or above, all positions with EDT above the set limit lay within the acceptable limits. The ADPI itself may not be adequate to describe either air diffusion performance or draft risk as the same value of 65% was recorded when the air supply flow rates were 0.1435 $m^3\ s^{-1}$ and 0.4896 $m^3\ s^{-1}$.

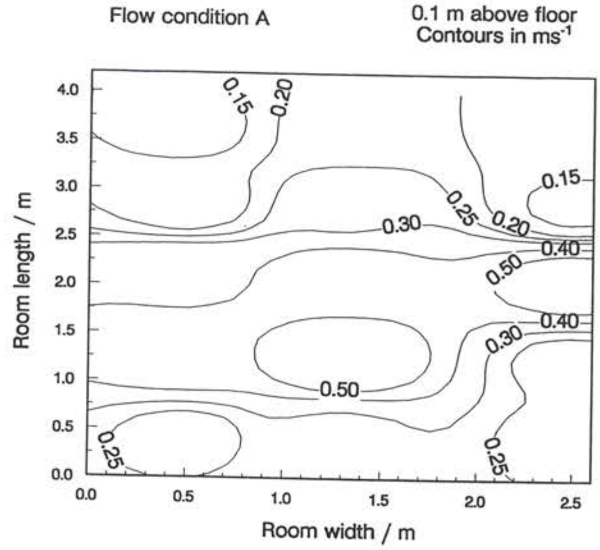

Fig. 3a. Air speed contours at the ankle level in the environmental chamber at flow condition A.

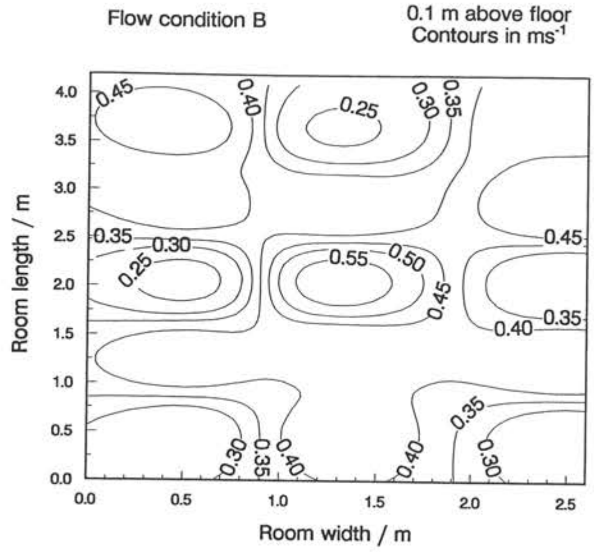

Fig. 4a. Air speed contours at the ankle level in the environmental chamber at flow condition B.

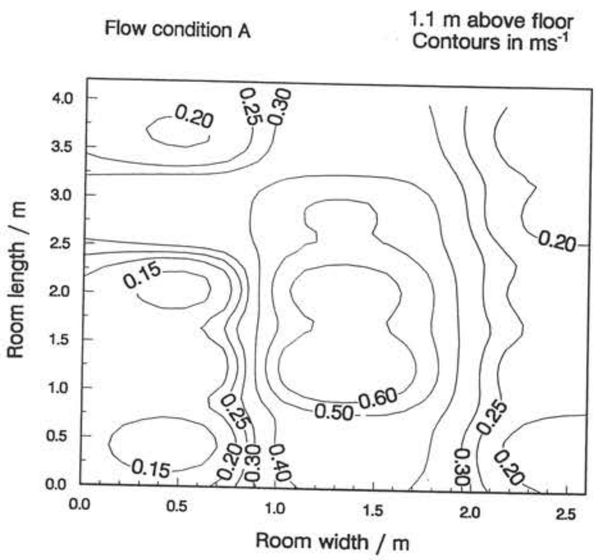

Fig. 3b. Air speed contours at the sitting head level in the environmental chamber at flow condition A.

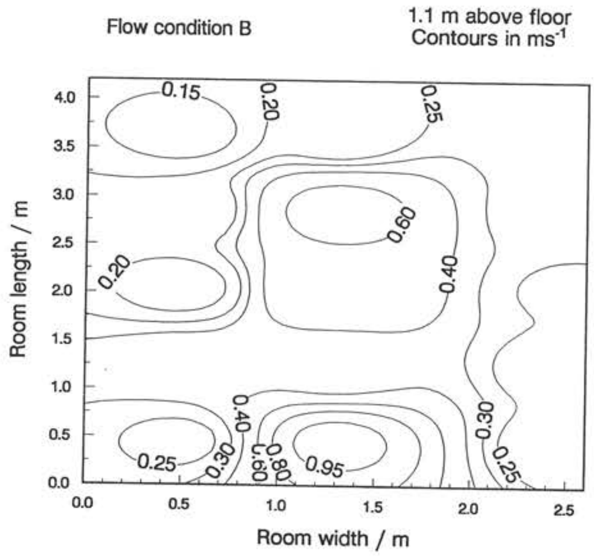

Fig. 4b. Air speed contours at the sitting head level in the environmental chamber at flow condition B.

A percentage distribution of the turbulence intensity is shown in Fig. 6. Most of the data fell into the medium to high turbulence zone as defined by Fanger *et al.* [11], i.e. about 35% to 55%. The turbulence intensity at a measuring point is plotted as a function of the mean air speed at that point in Fig. 7. As pointed out by Fanger *et al.* [11], the turbulence intensity depends on the mean air speed. It is observed that the turbulence intensity decreased as the mean air speed increased up to 1.5 m s^{-1}. This is similar to the curves measured by Thorshauge [16] and Fanger and Christensen [17], and both are shown in Fig. 7.

Further, the data are classified as high turbulence ($Tu > 55\%$), medium turbulence ($35\% > Tu > 20\%$) and low turbulence ($Tu < 20\%$) and plotted against the mean air speed in Fig. 8. The result reported by Fanger *et al.* [11] is also plotted for comparison. The range of air speeds for the low turbulence region in this study did not match with those of Fanger *et al.* [11] and comparison cannot be made. For the medium turbulence region, agreement between experiments is quite good. In the high turbulence region, the results reported by Fanger *et al.* [11] fell within the data range measured in this study.

The percentage dissatisfied is shown in Fig. 9. It can be seen that 90% of data fall below 37% dissatisfied for the environmental chamber under condition B.

Concerning the macroscopic numbers, the Archimedes number calculated using equations (2) with characteristic lengths l given by (3) and (5) are shown in Table 2. Values varied from 12.3 to 143.3 using equation (3), and 1.0 up

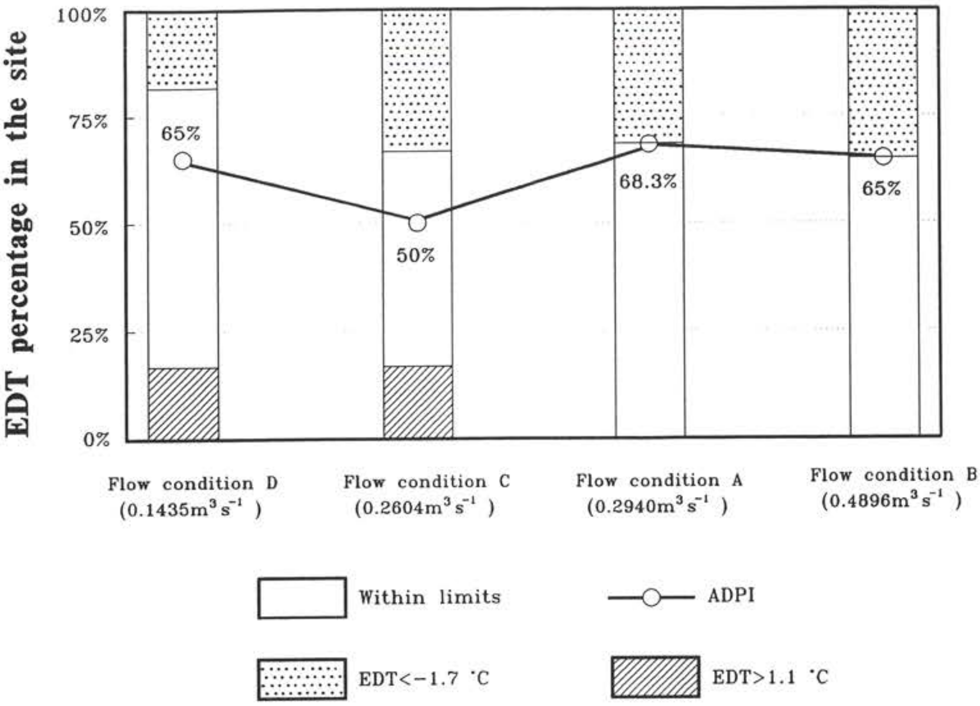

Fig. 5. Air diffusion performance index (ADPI) and effective draft temperature (EDT).

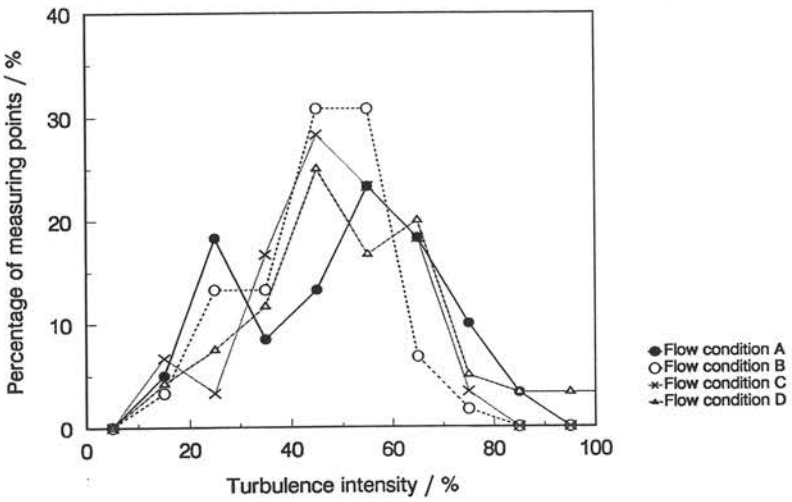

Fig. 6. Turbulence intensity distribution.

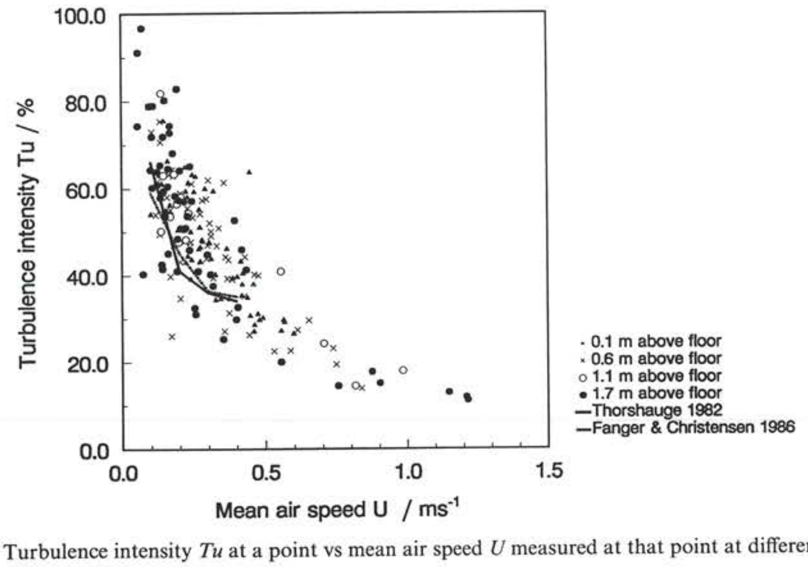

Fig. 7. Turbulence intensity *Tu* at a point vs mean air speed *U* measured at that point at different levels.

Table 2. Summary of parameters

Flow conditions	Flow rate/ $m^3\,s^{-1}$	T_1/°C	T_2/°C	Characteristic velocity V/m s^{-1}	Archimedes No. 1 Ar: $l = D = 2.323$ m	Archimedes No. 2 Ar: $l = \frac{ab}{D} = 0.586$ m	Corrected Archimedes No. Ar_c	Reynolds No. Re	Jet No. J	Throw y/m	ADPI/%
D	0.1435	19.50	20.77	0.02628	143.3	11.5	0.549	3777.7	2.08×10^{-4}	0.30	65.0
C	0.2604	18.50	20.74	0.04769	77.0	6.2	0.295	6855.2	6.87×10^{-4}	0.45	50.0
A	0.2940	21.00	22.09	0.05385	29.1	2.3	0.112	7739.7	8.74×10^{-4}	0.60	68.3
B	0.4896	19.50	20.77	0.08967	12.3	1.0	0.047	12889.0	3.03×10^{-3}	0.75	65.0

$B = 2.6$ m, $H = 2.1$ m, $a = 0.146$ m, $b = 2.955$ m, $V_{Room} = 22.386$ m^3.

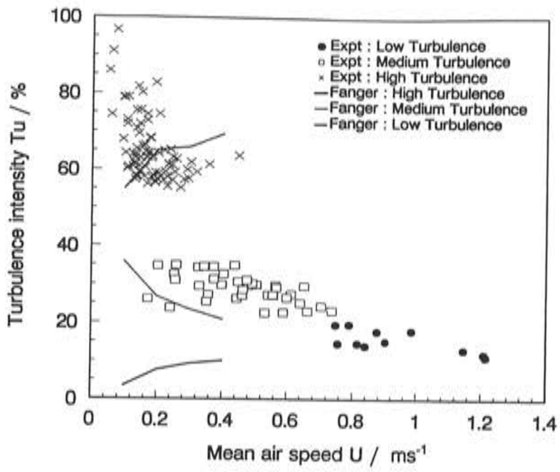

Fig. 8. Turbulence intensity Tu at a point vs mean air speed U and grouped as low, medium and high turbulence.

to 11.5 from equation (5). The expression (5) is used for calculating the characteristic length l here as the diffuser dimension is specified. The Reynolds number is shown also in Table 2 and the higher the flow rate, the larger is the Reynolds number.

The jet numbers at different flow conditions are also calculated and shown in Table 2. The higher the flow rate, the higher is the jet number. Although this number is defined by Barber *et al.* [15] for evaluating the air diffuser design, its correlation with the ADPI is not obvious as demonstrated in Fig. 10.

Another important parameter for predicting air distribution is the 'throw' (Whittle [3], Jackman [4]). The throw y is defined to be the horizontal distance from the outlet of the air jet to a cross-sectional plane perpendicular to the air flow where the maximum velocity of the air stream has been reduced to a selected terminal velocity of 0.25 m s^{-1}. For the diffuser used in the environmental chamber, the measured values of the throw are 0.30 m for condition D, 0.45 m for condition C, 0.60 m for condition A and 0.75 m for condition B. They are plotted in Fig. 11 against the corrected Archimedes number Ar_c defined by Randall and Battams [8] as

$$Ar_c = \frac{Ar0.6ab}{D^2}. \tag{14}$$

A linear regression of the following form is obtained:

$$y = -0.8352Ar_c + 0.7344. \tag{15}$$

Obviously, there is some correlation between the throw and the corrected Archimedes number.

5. CONCLUSIONS

Experimental studies on the air speed induced by a linear diffuser in an environmental chamber were studied under four flow conditions. Over one hundred and eighty thousand data points for air speed were measured at four heights above floor level. The air diffusion performance index and the predicted percentage dissatisfied were assessed. Macroscopic numbers, i.e. the Archimedes

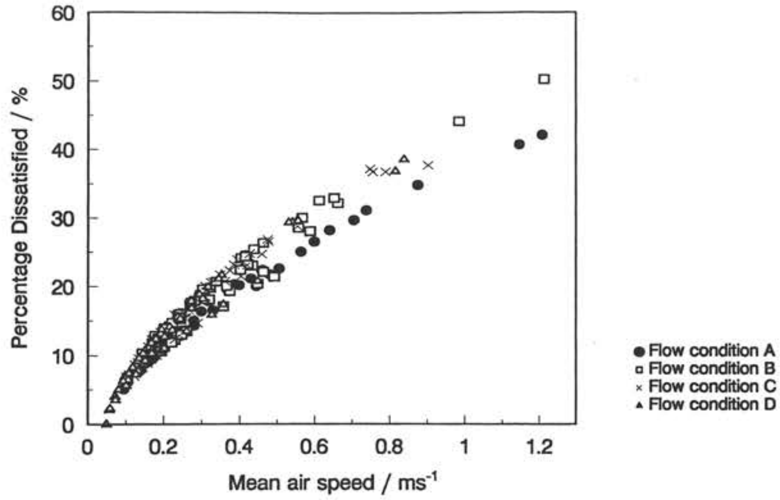

Fig. 9. Percentage dissatisfied at the chamber.

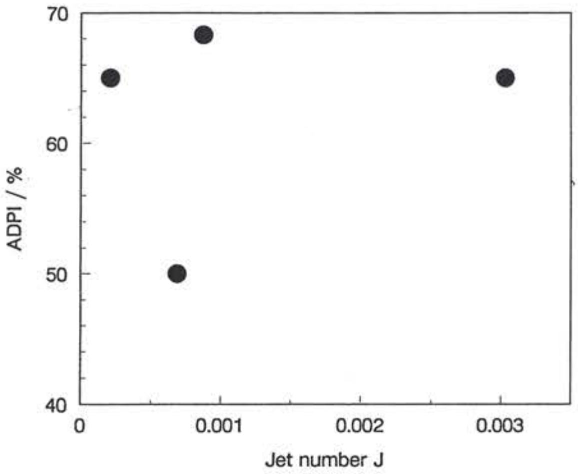

Fig. 10. ADPI vs jet number J.

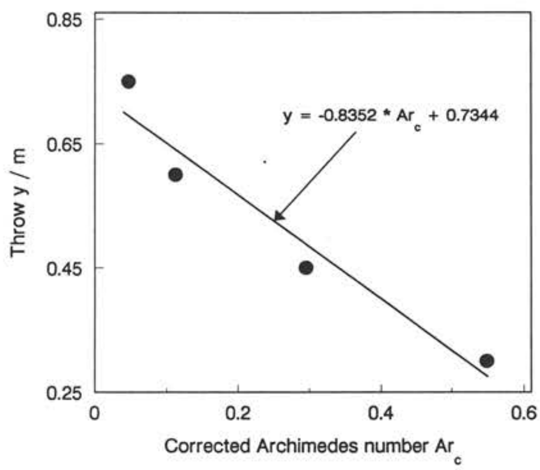

Fig. 11. Throw against corrected Archimedes number.

number, the Reynolds number and the jet number, were also studied. Both the Reynolds number and the jet number increased as the total supply flow rate increased, but the Archimedes number decreased while increasing the flow rates. There is no obvious correlation between the air diffusion performance index and the jet number. The throw of the diffuser is linearly related with the corrected Archimedes number. Further work on this would be in an air indoor airflow chamber of length 9 m, width 9 m and height 6 m.

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