VENTILATION SYSTEM PERFORMANCE

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Paper 37

VENTILATION CHARACTERISTICS OF SELECTED TYPE OF BUILDINGS AND INDOOR CLIMATE

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SYNOPSIS

The paper presents results of ventilation characteristics of a lecture/seminar room obtained by various door-window opening combinations and positions, and the level of comfort and air quality resulted by the given window-ventilating modes. Applying statistical methods, formulae of air change rate for the test room under it´s normal operating condition i.e. when all window and external door are shut and when particular windows are opened is also presented and graphs in relation to dominancy factors such as wind and buoyancy effects, are given. It is found that, under it´s normal operating mode the natural supply of outdoor air is far too deficient for health and comfort purposes. Means of improving the thermal environment and indoor quality to meet the fresh air requirements as recommended by both the ASHRAE and CIBSE Guides are suggested by proper selection of window opening patterns. Assessements of thermal comfort using a thermal comfort meter and occupancy odour or freshness were also conducted.

1. Introduction

As buildings become better insulated the energy demand becomes more dependent upon ventilation losses. However, if the building is too tight this may result in a deficiency because the fresh air supply has to be sufficient to ensure a comfortable and healthy indoor climate. If this can be achieved using naturally ventilated buildings, then this is more energy and cost effective. In the United Kingdom, almost all school buildings are ventilated by natural means, with windows as the usual means for fresh air supply as well as providing daylighting. However, there is not much information with regards to how users of buildings should operate natural ventilation openings, as means of ventilation control. Many users complaints could be reduced if they ´understood´ their building better, but designers have to bear in mind that the occupants are in the building to do a particular job, and operating the building is not necessarily their concern. Occupants´ involvement must only be for simple and common-sense operations; particularly that relating to health, safety and comfort. Clear instructions are essential, even if the mechanisms are obvious, such as which windows to open and by how much. Ways of giving visual representation also need developing.

The essence of this study is to investigate ventilation characteristics and hence the effects of natural ventilation via windows, doors and spaces linked by corridor or passage-ways. This particular lay-out is common in school buildings. Once schools are built the floor plan is rarely changed so that the effects of natural ventilation via windows and doors linked by corridor and entrances takes on particular characteristics for each location. This effect plus the occupancy behaviour and the effects of building orientation, meteorological and surrounding terrains can account for significant differences in ventilation characteristics, and hence the indoor climate and energy needs between otherwise similar school buildings.

2. Experimental Set-up and Instrumentations

The test room is a classroom known as the Synoptic Laboratory in the Department of Meteorology; measuring 10.9 m x 11.0 m and floor to ceiling height 3.05m. The experimentation plan layout and set-up is as shown in Figure 1. Twenty-four thermistor probes are employed to measure the room and outside air temperatures (dry and wet-bulb) and globe temperatures. Three vane cup anemometers are installed on the roof of the test room, at a height 0.5 m and located on the north, south and east walls respectively. Wind direction is measured by a wind vane located on the centre of the roof, at a height 1.95 m. Global solar radiation is measured by a solarimeter also located on the roof of the test room. Resistance switches are fitted to six doors; two on the main entrance doors and the rest on interior doors. A Bruel&Kjaer Type 1212 Comfort Meter is used to evaluate the thermal environmental quality using the predicted mean vote (pmv) scale as an index of comfort. A Dantec Type 54N10 thermal anemometer was used to measure the room air velocity at several points 0.9 m above the floor. An infra-red gas analyser is used for monitoring the carbon dioxide level in the test room and also for measuring the tracer gas decay during ventilation rate measurement. Output from the infra red analyser is fed into a flat-bed chart recorder.

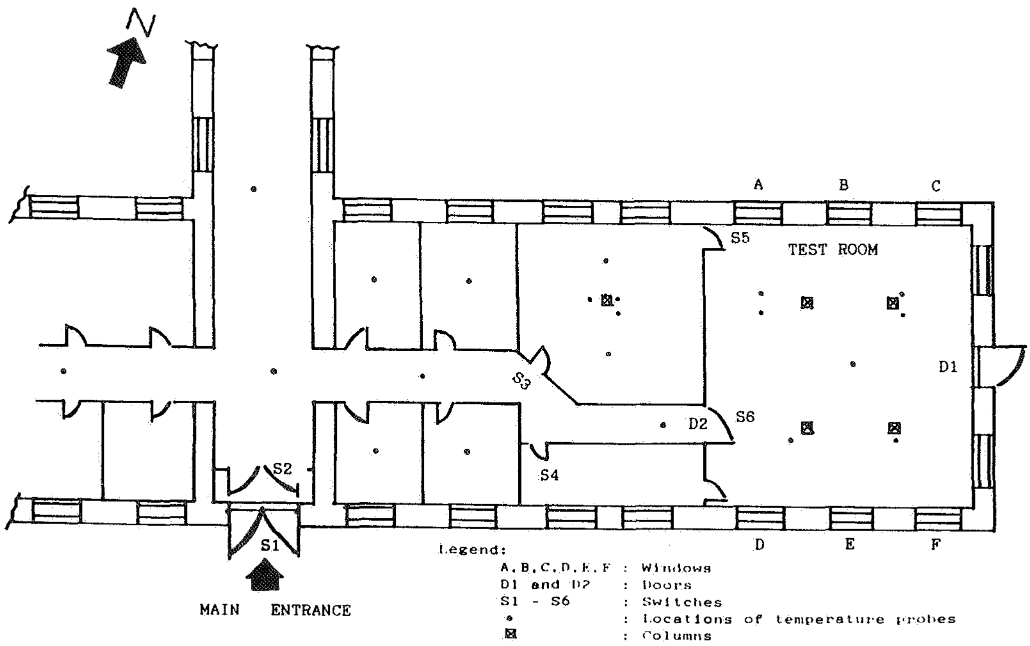

Fig.1. The Test Room and Experimental Set-Up

Data are logged on a BBC B microcomputer via a 32-channel multiplexer feeding into a 13-bit bipolar analogue converter (ADC) connected to the 1 MHz bus port of the computer. The ADC has a basic range of + 2.048 V, and its resolution was 0.5 mV. The program scanned all or a sub-set of the channels, applied calibration factors to the measured voltages, calculated means and standard deviations of all variables over a specified period, and saved the results to disc. A time interval of 1 hour was used for the purpose of this study. Another 32-channel chart recorder and data logger, Molytek Type 2702 was used to record the outputs from the thermal comfort meter as well as the temperatures of the test room.

3.Method

A series of ventilation rate measurements of the test room are conducted using the concentration decay method with carbon dioxide (CO2) as the tracer gas. Air change rates of particular combinations of windows and their opening positions are measured to investigate the variation in the ventilation characteristics, representing basically the two common types of ventilation i.e. single-sided or cross-ventilation. The air flow pattern for several window opening combinations is also established by measuring the velocity and turbulence at several points in the room and hence, the discomfort i.e. the percentage dissatisfied (PD) due to draught was evaluated. A total of 72 identical experiments were conducted without opening any windows or doors and a statistical model of ventilation rate derived using a multiple regression technique. This was the normal mode of usage of the room during the heating season. Carbon dioxide levels were also monitored during the occupancy periods as a means of assessing the indoor air quality in order to establish a rational basis for ventilation of spaces where body odour is the major pollutant.

A subjective survey of occupants was undertaken; the occupants were asked to vote on their sensations of the thermal environment including impressions of odour based on the ASHRAE seven-point thermal sensation scale. The first group of 46 subjects includes 10 females and 36 males; age range was between 22 - 40 years (comprising of Asian, African, British and South American Nationalities). They were the normal users of the room, participated in the test which was conducted under the normal operating mode of the room, in mid-March 1990. The second subjective test on 18 occupants; age between 22 - 40 years and of various nationalities, was conducted when two diagonally opposite windows (D & E) were opened one-half opening position, at the end of July 1990. The sample of questionnaires for the subjective analysis is as shown in Appendix 2.

4. Results and Discussion

4.1. Statistical Model of Ventilation

A statistical model of ventilation rate of the test room under it´s normal operating mode i.e. when all window are closed and internal door (D2) occasionally opened is given by the equation:

$$N = 0.092 - (0.37\times10^{-3}\Delta T) + (0.26\times10^{-3}\,\theta) + 0.019\,V^{2} \qquad (1)$$

where:

N: air change rate (h)

ΔT: difference between indoor and outdoor temperature (K)

θ: wind direction, taken from true North (degree)

V: local wind speed (m/s)

The governing equation for the case when windows are opened is:

$$N = 1.44 + 4.65A + 0.59\,V^{2} - 0.013\,\theta - 0.023\,\Delta T \qquad (2)$$

where:

A: area of window opening (m^2)

From the test of significance (see the t-test as shown in Tables 1a and 1b) the air change rate is much influenced by the wind factors i.e. speed and direction, and window opening area rather than the temperature difference.

Table 1a. Regression Coefficients

Y-variate : N

Parameter	Estimate	SE	t
Constant	0.09221	0.04904	1.9
θ	0.00026	0.00015	-0.1
ΔT	0.00037	0.00392	1.8
V^2	0.01907	0.00366	5.2

Table 1b. Regression Coefficients

Y-variate: N

Parameter	Estimate	SE	t
Constant	1.4421	1.5068	1.0
θ	-0.01325	0.00549	-2.4
ΔT	-0.02342	0.12011	-0.2
V^2	0.59414	0.28436	2.1
A	4.6471	1.2691	3.7

The plot of air change rate for a range of wind speed and temperature difference ΔT = 0, 7.5, 15.0 and 20.0 K and wind direction θ = 90 and 270 deg. using both equations (1) and (2) is shown in Figures 2a and 2b.

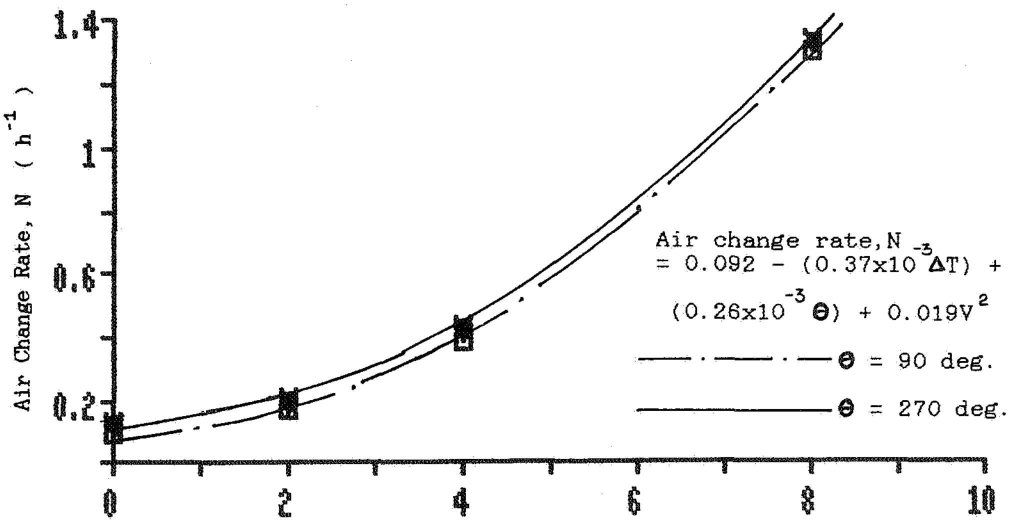

Fig.2a. Predicted Variation of Test Room Air Change Rate with Wind Speed and Temperature Difference when no Window is Open

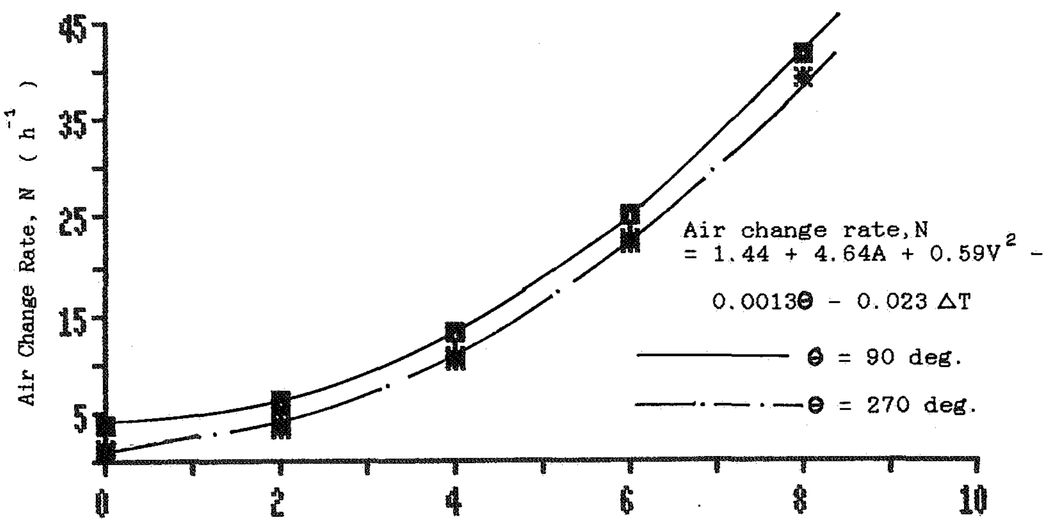

Fig.2b. Predicted Variation of Test Room Air Change Rate with Wind Speed and Temperature Difference when Windows are One-half Open

From Figure 2b, for a local wind speed of 1.8 -2.0 m/s and opening area equivalent to two windows opened by one-half opening position, would produce the required fresh air supply as recommended in the ASHRAE and CIBSE guides.

4.2.Ventilation Characteristics

4.2.1.Under Normal Occupancy Mode

The mean value of air change rate attainable during a normal operating mode of the room i.e. when all windows are shut and internal door (D2) is ocassionally opened, is 0.2 per hour (19.5 l/s). This far too low for comfort and health purposes. As recommended by the ASHREA (7) and CIBSE (8) Guides for the control of body odour, the minimum air change rate should be in the order of 2.75 (265.9 l/s) and 2.6 (252.8 l/s) per hour respectively (Refer to Appendix 1 for calculation).

4.2.2.Ventilation Characteristics Due To Window and Door Opening

The results for the various window combinations and opening modes are summarised in Fig.3a and those due to door opening in Fig.3b.

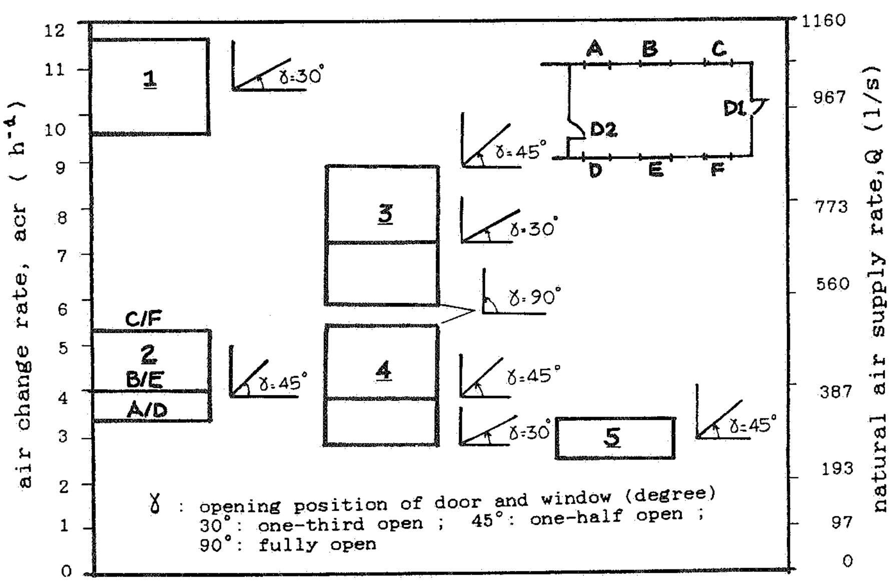

Fig.3a. Ventilation Characteristics of Windows
Local wind speed: 0.8 - 2.2 m/s; direction: 60 - 296 deg.
Legend:
1: All windows on north and south walls are opened
2: Directly opposite windows (A&D,B&E,C&F) are opened
3: All windows (A,B,C) on north wall are opened
4: All windows (c,D,E) On south wall are opened
5: Diagonally opposite windows (C&D) are opened
Note: Q = (3600 x acr (h^{-1})) / Room Volume (m^3)

Air change rate between 2.4 - 11.6 per hour (232 - 1121 l/s) is attainable for the various window combinations and opening positions for local wind speed between 0.84 - 2.22 m/s, direction 60 - 296 deg. from true North. The larger value is obtained when all windows on the north and south walls are opened by one-third of full opening position simultaneously and the main door of the test room is fully open (shown as item 1, Fig.3a). This to some extent includes the effect of the corridor which linked the room to the main enrtance. These results show that cross-ventilation i.e. by opening windows directly opposite each other, produces higher ventilation rates.

Another form of cross-ventilation i.e. by opening two diagonally opposite windows (C & D) produced moderate air change rates of 2.4 - 3.3 per hour (271 - 851 l/s), in the mid-opening position, at wind speed of 0.75 - 1.75 m/s, direction 147 - 285 deg. from North (shown as item 5, Fig.3a). Single-sided ventilation is studied by opening all windows on either the north or south wall and results as shown by items 3 and 4, Fig. 3a.

This mode of ventilation produced air changes between 2.8 - 8.8 per hour (271 - 851 l/s), wind speed range of 1.13 - 2.23 m/s and direction 60 - 296 deg.

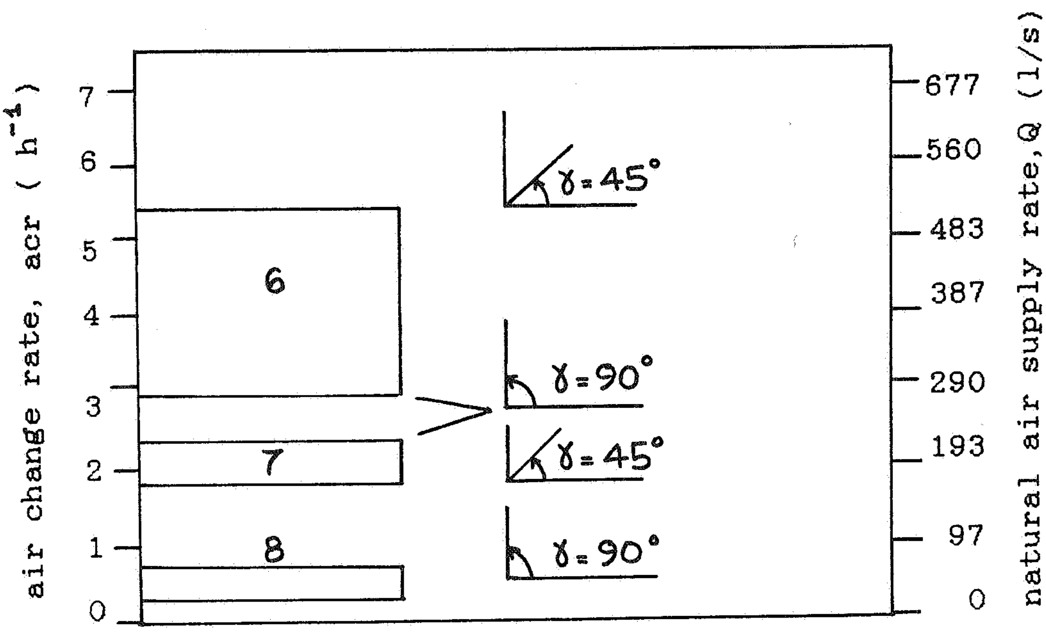

Fig.3b. Ventilation Characteristics of Doors
Local wind speed: 0.8 - 2.2 m/s; direction: 215 - 274 deg.
Legend:
6: Both external and internal (D1&D2) doors are opened
7: Only external door (D1) is opened
8: Only internal door (D2) is opened
Note: $Q = 3600 \times acr\ (h^{-1}) / \text{Room Volume}\ (m^3)$

The ventilation characteristic due to door opening varied from 0.3 to 5.4 air changes per hour (77 - 522 l/s) for a wind speed range of 1.40 - 2.44 m/s and direction 215 - 274 deg. The larger value was due to opening both the external and internal doors (D1 & D2) in the mid-opening position while the lower value was the result of opening only the internal door in it´s full position. The results are designated as items 6,7 & 8 in Fig.3b. It is important to note from these results the effect of building orientantion vis a vis to the window location and prevailing wind. The generally larger values of air changes when a window or a door was opened in the mid-position rather than in the full-position indicates that chanelling of air through an opening depend on the position of the window relative to the prevailing wind.

4.3.Thermal Environment and Indoor Air Quality

The results of thermal environment and air quality monitoring and subjective studies of the room under it´s normal occupancy mode i.e. without opening any windows or doors are summarised in Table 2.

According to Fanger and Berg Munch(1), and Cain et al(5), the indoor air quality of the test room is not acceptable i.e. more than 20% of the occupants are likely to complain or feel dissatisfied due to odour. However from Muhaxheri´s(3) findings the indoor air of the test room is acceptable.(Note: Values of odour intensity and percentage dissatisfied are extraploted from the results of these researchers using the value of carbon dioxide level monitored during the period of occupancy). For further explaintion refer to Reference (8).

Table 2.Odour Intensity (I) and Percentage Dissatisfied (PD) Votes of the test room

Odour Intensity (I)	Percentage Dissatisfied (PD)	Source
1.9	28 %	Fanger & Berg Munch (1)
1.8, 2.5, 3.1	n.a.	Yaglou (2)
1.5, 2.8	n.a.	Narasaki (4)
1.5	12 %	Muhaxheri (3)
n.a.	22 %	Cain et al (5)
n.a	6 - 12 %	Comfort Meter

The subjective assessment by 46 occupants of the thermal environment and indoor air quality of the room under its´ normal occupancy mode i.e. when all windows and door are closed, produced a total of 73.9 % dissatisfied due to feeling slightly warm to hot, and slightly cool. Taking "moderate odour" i.e. value of 2 on the odour sensation scale and"slightly stuffy" i.e value of 1 on the freshness-stale scale, as the base line values in assessing the acceptance of odour and fresh-stale quality of the indoor air, reveals that 24% and 52.2% are dissatisfied with the indoor environment due to body odour and staleness of the air respectively. This corresponds to 21.7% non-acceptance of the indoor air quality of the room if occupants are to be exposed to the indoor condition during their daily working period. The results are as shown in column 1 Tables 3a,b,c,d. When two diagonally opposite windows (D & E) were opened by one-half opening position, 55.6% of occupants were dissatisfied due to feeling slightly cool to warm, 17.6% are dissatisfied with the indoor environment due to the presence of body odour and staleness of the air respectively. On the overall acceptance, 88.2% voted that the indoor air quality was acceptable. The results are given in column 2 in Tables 3a,b,c,d. This particular combination of window opening was tested because it is the appropriate combination which could meet the recommended air changes i.e. 2.6 - 3.0 per hour, for comfort and odour control. The results of the thermal environment and air quality assessments for both situations, i.e. when the room is operated with and without opening windows, as a comparison, are also shown in Tables 3a,b,c and d.

Table 3.a:Comparison of Results of Subjective Analysis of Thermal Environment

Thermal Sensation Scale	With-out Opening Window		With Opening Window	
	No. of Occupants (%)	Dissatisfied (%)	No. of Occupants (%)	Dissatisfied (%)
3(Hot)	3 (6.5)		0 (0)	
2(Warm)	12 (26.1)		1 (5.6)	5.6
1(Slightly Warm)	14 (30.4)	(63.0)	5 (27.8)	27.8
0(Neutral)	12 (26.1)		8 (44.4)	
-1(Slightly Cool)	5 (10.9)	(10.9)	4 (22.2)	22.2
-2(Cool)	0 (0)		0 (0)	
-3(Cold)	0 (0)		0 (0)	
Total Dissatisfied		**73.9**		**55.6**

Table 3.b:Comparison of Results of Indoor Air Odour Perception

Odour Sensation Scale	With-out Opening Window		With Opening Window	
	No. of Occupants (%)	Dissatisfied (%)	No. of Occupants (%)	Dissatisfied (%)
0(No Odour)	18 (39.0)		8 (47.1)	
1(Slight)	17 (37.0)		6 (35.3)	
2(Moderate)	8 (17.4)	17.4	3 (17.6)	17.6
3(Strong)	1 (2.2)	2.2	0 (0)	
4(V.Strong)	1 (2.2)	2.2	0 (0)	
5(Over Powering)	1 (2.2)	2.2	0 (0)	
Total Dissatisfied		**24.0%**		**17.6**

Table 3.c:Comparison of Results of Indoor Air Freshness-Stale Perception

Freshness Stale Scale	With-out Opening Window: No. of Occupants (%)	With-out Opening Window: Dissatisfied (%)	With Opening Window: No. of Occupants (%)	With Opening Window: Dissatisfied (%)
-2(Very Fresh)	0 (0)		0 (0)	
-1(Fresh)	4 (8.7)		6 (35.3)	
0(Neutral)	18 (39.1)		8 (47.6)	
1(Slightly Stuffy)	18 (39.1)	39.1	3 (17.6)	17.6
2(Stuffy)	6 (13.1)	13.1	0 (0)	
Total Dissatisfied		**52.2**		**17.6**

Table 3.d:Comparison of Results of Indoor Air Acceptance

Acceptance Scale	With-out Opening Window: No. of Occupants (%)	With Opening Window: No. of Occupants(%)
0 (Acceptable)	36 (78.3)	15 (88.2)
1 (Not Acceptable)	10 (21.7)	2 (11.8)
Total Acceptance	**78.3**	**88.2**

Notes: The first subjective assessment was conducted under room temperature between 20.3 - 23.4 °C, relative humidity between 80 - 85%, air change rate < 0.5 h^{-1}, indoor carbon dioxide level 116 - 1460 ppm above outdoor, local wind speed 3.6 m/s and direction 320 from North and predicted mean vote(pmv) = - 0.6.

The second subjective assessment was conducted under room temperature about 24.4 ° C, relative humidity 58%, indoor carbon dioxide level 425 ppm above outdoor, local wind speed 1.90 m/s and direction 340 ° from North and predicted mean vote(pmv) = 0.5

The possibility of discomfort due to draught caused by air turbulence is also investigated by calculating the percentage dissatisfied (PD) level at various points in the test room. The PD level as proposed by Madson et al (9) is given by the equation,

$$PD = (3.14 + 0.37 \times V \times Tu)(34 - Ta)(V - 0.05)^{0.62} \quad (3)$$

which is a function of air temperature Ta, mean air velocity V, and turbulence intensity Tu, and valid for:

$20\ C < Ta < 26\ C$
$0.05 < V < 0.4\ m/s$
$0 < Tu < 70\ \%$

The PD levels were found to be less than 6% at all points in the room when windows C and D were opened in the mid-position as shown in Figure 4.

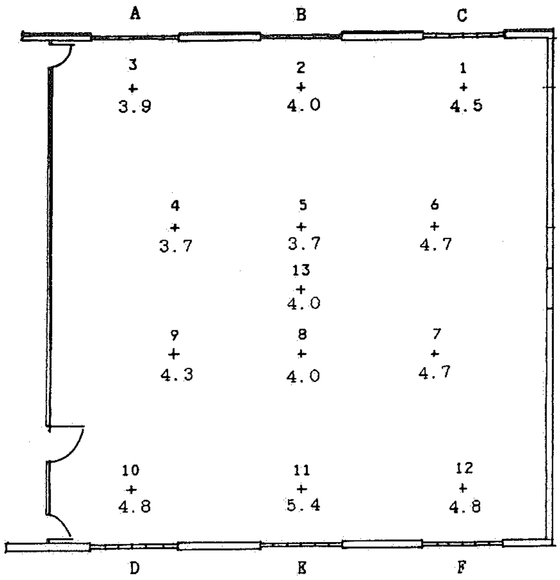

Fig.4. Percentage Dissatisfied (PD) Level due to Draught in Test Room when Two Diagonally Opposite Windows are Opened

Comparison of PD levels in the room as a result of several combination of window opening is shown in Table 4. In all cases the PD levels were less than 10%, indicating that there is no likely discomfort cause by draught i.e. air motion as a result of window ventilating.

Table 4: Percentage Dissatisfied (PD) Level due to Draught

Point	Window Opening Combinations and Position of Opening			
	A & D 1/2-Open	B,D,F 1/2-Open	B,D,F Fully-Open	D,E,F Fully-Open
1	4.6	4.8	3.3	4.8
2	4.0	5.6	3.7	5.6
3	3.9	4.8	3.5	4.8
4	3.7	3.9	3.4	3.9
5	3.7	4.1	3.9	4.1
6	4.7	4.9	3.3	4.9
7	4.7	6.2	3.4	6.2
8	4.0	4.9	3.7	4.9
9	4.3	4.2	4.4	4.2
10	4.8	5.4	3.6	5.4
11	5.4	5.5	3.4	5.1
12	4.8	6.2	4.5	6.2
13	4.0	4.8	3.8	4.8

4. Conclusions

This study shows that the ventilation characteristic of naturally ventilated spaces can be varied by applying different modes of window-door opening patterns. The information gathered would be useful for managing buildings during the warm season, where some means of controlling the indoor climate can be achieved by windows opening. If the result of air change rate measurements for the normal mode of operation of the test room during the heating season is to hold true for school classrooms (i.e. < 0.5 air change rate per hour), this is far too deficient for health and comfort purposes. This study also reveals the importance of building planning i.e. planning layout of building in order to enhance the useage of natural ventilation for both comfort and indoor air quality control.

5. Future Work

- An important aspect of comfort is room air movement due to various window types and operating modes; this will be studied next.

- Investigation will also be carried out on other buildings with distinctive plan lay-out and different window types and arrangements in order to investigate the ventilation characteristics of various window styles in relation to air movement control for comfort.

Acknowledgements

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APPENDIX 1

Estimation of the mininum fresh air requirement for test room according to ASHRAE and CIBSE recommendations (revised)

Air change rate, N = (3600 x Q) / V per hour

where:

Q : Volume flow rate of air (m / s)

V : Volume of test room (m^3) (365.7)

ASHRAE recommendation : 8.0 l/s per person

CIBSE recommendation : 7.5 l/s per person

Normal occupancy of test room is 35 people

N (ASHRAE) = (3600 x 8 x 10)(35 x 10) / 365.7
= 2.75 per hour

N (CIBSE) = (3600 x 7.5 x 10)(35 x 10) / 365.7
= 2.60 per hour

APPENDIX 2

INDOOR CLIMATE INVESTIGATION: SUBJECTIVE SURVEY

Date:________ Day:________ Time:________

Building/Room: ____

Please answer the following questions by putting a tick at the appropriate boxes. Your answers will be treated confidentially.

Question 1. What clothing are you wearing ?

Shirt :	Long-sleeve	☐	Short-sleeve	☐
Trousers:	Thick material	☐	Light material	☐
Sweater/Cardigan:	V-neck	☐	Round-neck	☐
	Wool	☐	Others	☐
Skirt:	Wool	☐	Others	☐

Question 2. Sex: Male ☐ Female ☐

Question 3. Nationality : ______________________

Question 4. When did you last have your bath or shower ?

_______ day/s ago.

Question 5. When did you last change your clothings ?

_______ day/s ago.

Question 6. How do you feel about the temperature in this room ?

	Beginning of class	End of class
hot	☐	☐
warm	☐	☐
slightly warm	☐	☐
neutral	☐	☐
slightly cool	☐	☐
cool	☐	☐
cold	☐	☐

Question 7. How strong is the odour ?

	Beginning of class	End of class
no odour	☐	☐
slight odour	☐	☐
moderate odour	☐	☐
strong odour	☐	☐
very strong odour	☐	☐
over powering odour	☐	☐

Question 8. Imagine that during your daily work you would be exposed to the present odour. Would you judge the odour af the air as :

acceptable	☐	☐
not acceptable	☐	☐

Question 9. Do you think the air is fresh ?

very fresh	☐	☐
fresh	☐	☐
neutral	☐	☐
slightly stuffy	☐	☐
stuffy	☐	☐

Other Comments: