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The Effects of Room Orientation on Indoor Air Movement in the Warm-Humid Tropics: Scope for Energy Savings

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Abstract

This paper examines the effects of prevailing wind on room orientation and placement of windows, in a warm-humid setting like Dhaka. In humid climates one heavily depends on air movement to provide thermal comfort. The paper is based on a wind tunnel experiment, conducted in UK by the author, on the model of an existing test house in Dhaka, to determine pressure coefficients, from which indoor air movement under different inlet-outlet combinations were calculated for the worst situation scenario, ie, 3 pm readings of air speed and humidity. Calculated indoor air movement values were then assessed to determine comfort potential, and whether other sources of air movement using active energy, are needed to provide thermal comfort air movement. The results are then analysed to provide guidelines for room orientation and for location of windows in buildings, which aim to reduce active energy expended for comfort of the occupants.

Introduction

It has often been argued that tropical countries like Bangladesh, which are warm and humid for long spells each year, should have settlements that allow for as much air movement as possible. Building design and orientation should be planned to catch the available breeze. However, wind directions in the region are not constant throughout the year, and often, available wind speeds are not sufficient to generate favourable indoor airflow. It is on the hottest, most humid days when conditions are still, that a building occupant most usually needs comfort in the form of air movement. Ironically though, it is on these very same days that calm conditions prevail and hence, available natural wind proves to be inadequate. This paper examines the ability of natural wind-speed and direction, in the course of an average year, to provide comfort conditions in building interiors for eight main orientations in a typical residential building in Dhaka. In the event that natural flow is adequate in providing air movement sufficient to ensure thermal comfort, the use of fans and other mechanical devices for cooling can be minimised, thereby affecting energy savings.

Table 1, which gives the prevailing wind velocities for locations in Dhaka[1, 2], averaged over twenty years[1], clearly indicates that during the humid months from June to September, when air movement is imperative for thermal comfort, the predominant wind direction is from the South and South East. Normally available data refers to wind speeds at a reference height of 10m on open ground. But wind speeds drop with height and the degree of urban development. Even when more detailed wind flow data can be obtained from meteorological stations, it is difficult to predict the exact wind pattern at a particular site. The general speed and direction of wind is modified by the presence of built-forms, vegetation and topography, all of which create a micro-climatic wind pattern unique to each particular site and circumstances.

In humid climates one heavily depends on air movement to provide thermal comfort. The quantity indoor of air entering the space (in terms of air change /hour etc) is not the prime factor in predicting comfort potential of an airflow situation. Here the pattern of flow and the velocity of flow are more indicative.

Table 1 Prevailing wind speed and direction in Dhaka, Bangladesh

Month	Wind speed m/sec	S	SW	W	NW	N	NE	E	SE
		Percentage of prevailing direction							
Jan	1.4	-	-	-	83	17	-	-	-
Feb	1.6	11	22	6	44	17	-	-	-
March	2.6	35	41	6	-	12	-	-	6
April	3.7	94	6	-	-	-	-	-	-
May	4.4	84	-	-	-	-	-	5	11
June	3.8	42	-	-	-	-	-	-	58
July	3.9	28	5	-	-	-	-	-	67
Aug	3.3	26	-	-	-	-	-	-	74
Sept	3.4	28	-	-	-	-	-	-	72
Oct	2.5	16	-	-	16	31	16	5	16
Nov	1.4	-	10	-	37	42	-	11	-
Dec	1.5	-	-	-	50	50	-	-	-
Yearly		30	7	1	19	14	1	2	25
Summer / rainy season		44	6	1	2	5	2	1	38
Winter (Nov-Feb)		3	8	1	54	31	-	3	-

Mechanism of Wind flow Through A Building

The pressure difference between any two points on a building envelop determines the potential driving force for ventilation, were openings provided at these points. Other than this pressure difference, the rate of airflow is also dependent upon the areas and resistances of the various apertures. When there are a number of openings in series, as in Fig 1, channelling a flow in from an inlet through an outlet, the total pressure difference between inlet and outlet is :

$$P_1 - P_4 = P_L \quad (1)$$

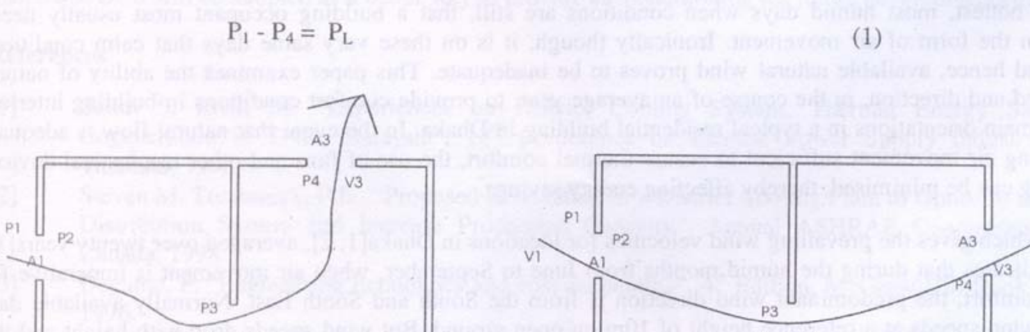

Fig .1 Air flow through opening in series

Where, the total pressure loss P_L is the difference between the pressures at point 1 and point 4. The pressure generated at any point on the surface of a building is dependent only upon the dynamic pressure of the upstream wind, ½ ρV^2, V being the mean wind speed at building height in meters per second. From this consideration a dimensionless pressure coefficient, C_p, emerges defined by the following expression:

$$C_p = (P_b - P_s) / ½ \rho V^2 \qquad (2)$$

where P_b and P_s are the mean pressure at any point on the building surface and the static pressure in the undisturbed wind respectively. The volumetric flow through any opening will also be regulated and resisted by a characteristic of the opening, expressed by its discharge coefficient, C_d, which is defined as:

$$C_d = 1 / C^{1/2} \qquad (3)$$

Values for both C_d and C have been published in the ASHRAE guide [1]. For a space with only two openings having windward and leeward pressure coefficients of C_{p1} and C_{p2} the volumetric flow rate Q, in cubic meter per second can be determined using the area of the opening A in square meters, from:

$$Q = C_d A ((C_{p1} - C_{p2}) V_z^2)^{1/2} \qquad (4)$$

For winds not perpendicular to the openings, the windward or inlet area can be corrected by the cosine of the wind incidence θ using the expression:

$$A_{1(cor)} = A_1 \cos \theta \qquad (5)$$

Applying the above equations [1], have used the general discharge equation given below to calculate the volumetric flow rate through openings in series of areas A_1, A_2..A_n, in housing in Papua New Guinea, for n number of openings:

$$Q = \left(\frac{(C_{p1} - C_{pn+1}) V_z^2}{\frac{1}{C_{d1}^2 A_1^2} + \frac{1}{C_{d2}^2 A_2^2} + \frac{1}{C_{dn}^2 A_n^2}} \right)^{1/2} \qquad (6)$$

where,

Q = volumetric flow rate
C_{pn} = pressure coefficient at point 'n'
C_{dn} = discharge coefficient at point 'n'
V_z = airspeed in m/sec

As climatic conditions in Papua New Guinea, are very similar to those existing in Bangladesh for much of the year, this present work has been structured on Aynsley's work, where relevant.

Application of the Discharge Equation to a Given Context

A wind tunnel experiment was conducted in Sheffield [1] on the solid model of a typical example residence of Dhaka shown in Fig 2. The aim of the study was to determine pressure coefficients at certain points on its surface, which could be used to calculate the volumetric flow rate for different combinations of openings at varying orientations, using the discharge equation given above. These pressure coefficients indicated the potential for airflow through the building. Inlet velocities were then obtained from the air-change rate. As the size of window opening in houses of Dhaka is typically quite large relative to the floor area of the room, it was considered that the calculated airspeed value at opening would be a reasonably reliable indicator of expected average indoor airspeeds.

From the calculated values of airspeed above, it was then ascertained whether the predicted internal airflow induced by natural means would be sufficient in creating comfortable conditions or not. This was done by making use of established comfort studies[i], which were adapted for Dhaka's conditions to determine the airspeeds necessary to restore thermal comfort during the months March to October. It is during this period of the year that increased airspeed can help to alleviate discomfort due to the hot and sticky environment.

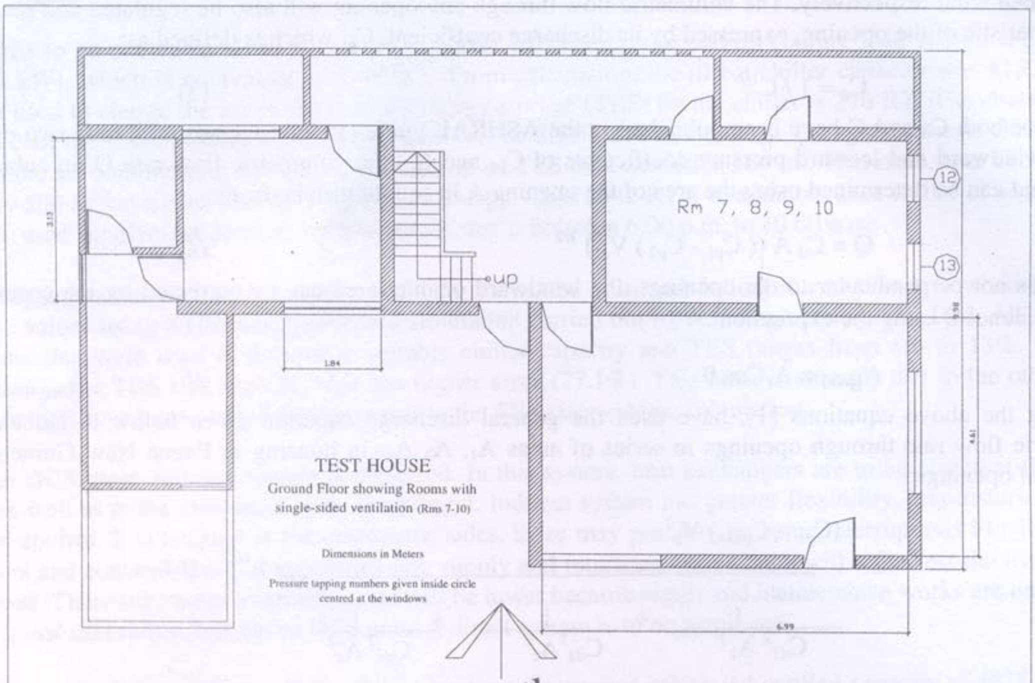

Fig 2 Plans of the test house

Description of the Example Residence and the Experiment

The example residence is U-shaped, sprawling in form, with a maximum of its wall surfaces left free for openings. West walls have the least area of openings. The two-storied building is elongated on the East-West Axis and incorporates a semi-enclosed internal courtyard, open on the South, which funnels the breeze in from the predominantly prevailing wind direction for most of the summer and monsoons. The walls are a combination of 250 mm and 125 mm brick masonry construction, plastered on both faces and white-washed. All openings, doors and windows, are netted up for mosquito protection and have security grilles. They are also provided with sunshades, which cut off some of the incident solar radiation and also protect the openings during light rain. When it rains heavily the windows are shut in order to prevent rain from penetrating into the interior.

A solid aluminium model of the test house in scale 1:50 was constructed and placed in a 1.2m x 1.2 m boundary layer wind tunnel. A boundary layer simulation arrangement was chosen which was judged most appropriate to represent the setting of the test house. 28 pressure tappings were placed on the model surface to represent the centre of the location of openings in the actual residence shown in Fig 3.

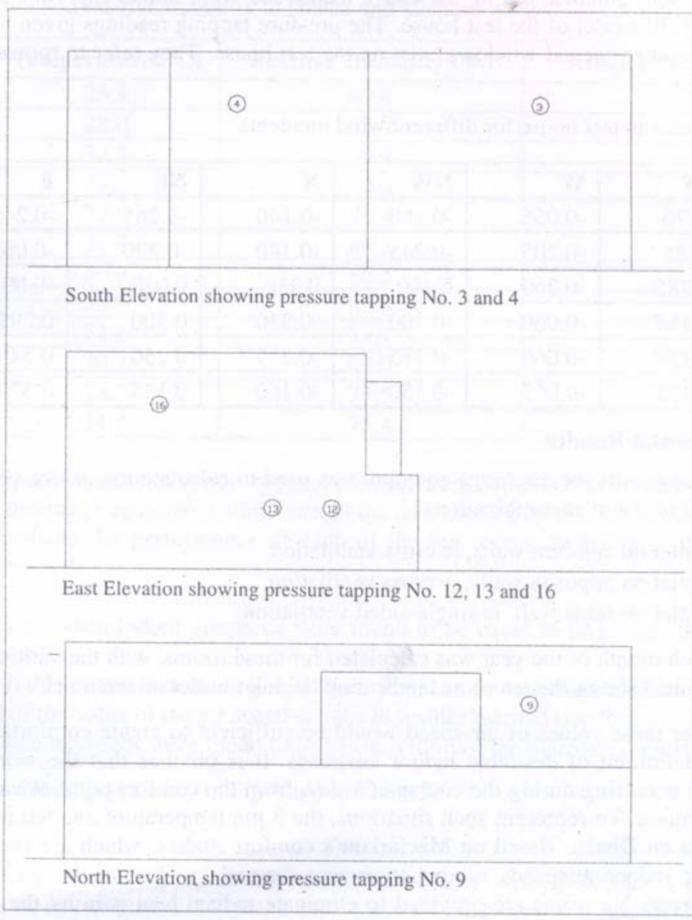

Fig 3 Positions of pressure tapping on the test house

Before the commencement of each set of readings, the velocity-pressure or the reference dynamic pressure in the free undisturbed airstream, upwind from the building, was noted from readings off a pitot tube, which was installed in the wind tunnel at a height of 800mm. This reading was verified half-way through and at the end of each set of readings. The CIBSE[ii] describe pressure coefficient, CP_1, as a dimensionless ratio of P_1, the pressure at any particular point of interest, to a reference dynamic pressure $1/2\ \rho V^2$ of the wind, measured at a nominated height in the undisturbed airstream, upwind from the building. Thus, in this case, CP_n is the ratio of reading at pressure tapping #n in pascals to the pitot tube reading also in pascals. Calculated pressure coefficients indicate potential wind-flow through the building, if openings were to be provided at the appropriate points. The greater the difference between the pressure coefficients at two points, the stronger is the expected flow between them. Discussion of pressure coefficients is provided above in Section "Mechanism of Windflow through a Building" above.

Eight sets of readings for each of the pressure tappings were obtained by rotating the model to face wind incidences of South, South-east, East, North east, North, North-west, West and South-west. The roof was always found to be in a negative pressure zone. The readings relevant to the discussion in this paper are given in Table 2. These readings were obtained during the above mentioned wind tunnel experiment directly from the tappings attached to the 1:50 model of the test house. The pressure tapping readings given in Table 2 relate to points on the solid model where actual windows exist on the test house. They refer to rooms with both single-sided and cross ventilation.

Table 2 Pressure coefficients in test house for different wind incidents

No.	S	SW	W	NW	N	NE	E	SE
3	0.445	0.170	-0.055	-0.180	-0.140	-0.265	-0.245	0.330
4	0.325	0.085	-0.205	-0.245	-0.140	-0.270	-0.085	0.205
9	-0.165	-0.285	-0.260	0.390	0.350	0.050	-0.095	-0.135
12	-0.150	-0.160	-0.060	-0.100	-0.330	0.300	0.295	0.135
13	-0.185	-0.150	-0.060	-0.115	-0.255	0.250	0.340	0.210
16	-0.385	-0.135	-0.065	-0.130	-0.160	0.145	0.375	0.340

Analysis of the Experimental Results

Based on the experimental results the discharge equation was used to calculate the indoor velocity of air in ten test rooms, for three basic inlet-outlet combinations:

- Inlet and outlet on adjacent walls, ie cross ventilation
- Inlet and outlet on opposite walls, ie cross ventilation
- Inlet and outlet on same wall, ie single-sided ventilation

The inlet air speed for each month of the year was calculated for these rooms, with the various combinations on different orientations. Table 3 shows the ten rooms indicating the inlet-outlet orientations.

In order to assess whether these values of air speed would be sufficient to create comfortable indoors it was necessary to attempt a definition of desirable indoor airspeeds. It is obvious that the worst combination of environmental conditions occurring during the course of a day, from the comfort point of view, is encountered in the middle of the afternoon. To represent such situations, the 3 pm temperature and humidity readings were taken from available data on Dhaka. Based on Macfarlane's comfort studies, which are considered extremely valid for the tropics, the indoor airspeeds needed to restore thermal comfort in the given conditions were derived, assuming that proper measures are provided to eliminate radiant heat gain by the occupants. This is shown in Table 4.

Table 3 Inlet outlet combinations in the house

Room no	Combination type	Windows on:	N	S	E	W
1	Windows on adjacent walls		-	y	y	-
2	Windows on adjacent walls		-	y	-	y
3	Windows on adjacent walls		y	-	y	-
4.	Windows on adjacent walls		y	-	-	y
5	Windows on opposite walls		y	y	-	-
6	Windows on opposite walls		-	-	y	y
7	Single-sided		-	y	-	-
8	Single-sided		-	-	y	-
9	Single-sided		-	-	-	y
10	Single-sided		y	-	-	-

Table 4 Temperature and relative humidity in Dhaka and airspeed needed for comfort

Month	Temperature (^{0}C)	Relative Humidity (%)	Airspeed for Comfort (m/sec)
January	25.3	69.4	-
February	28.0	62.4	-
March	32.5	59.0	0.6
April	34.2	70.0	1.35
May	32.9	78.4	1.22
June	31.3	86.5	0.85
July	30.9	86.3	0.77
August	30.9	85.9	0.73
September	31.3	85.9	0.80
October	30.7	83.0	0.64
November	28.7	77.5	
December	24.4	75.4	

These derived air speeds needed to restore thermal comfort were compared to the calculated values for airspeed, obtained from the discharge equation, within each of the test rooms with the different opening combinations and orientations. To evaluate the performance of each of the ten rooms, in terms of their comfort status, three situations were described:

- Comfortable: when indoor airspeeds were found to be equal to or greater than that needed to restore thermal comfort.
- Uncomfortable: when indoor airspeeds were found to be less than comfortable, but still greater than one-third of the value of the air speed needed to restore thermal comfort.
- Stuffy: when airspeeds were found to be below a third of the thermal comfort airspeed.

The comparison is shown graphically in Fig 4 and in Table 5.

Limitations

Only average values for wind speed and prevailing directions were available at the time of the research. However, the time of day chosen was 3 pm, a time when all the elements conspire to act against each other to produce the worst part of the day. This means that there is little likelihood of encountering more severe situations for most of the other parts of the day, though we may be likely to get worse 3 pm situations. So generally, provided comfort can be achieved at this time, the rest of the day will probably be comfortable.

For these calculations, it has been assumed that total flow will follow only the direction specified and that there will be no branching. In other words, the flow is expected to go from inlet to outlet taking any path within the volume of the room being tested. The effects of cracks or gaps around the door/window joints have not been considered. The assumption that doors will be shut is realistic for 3 pm in the afternoon as this is siesta time, and the inmates of a room would be in the privacy of the room.

Rooms 7 to 10 have only single sided ventilation, ie they each have only one exposed wall, but there are two windows on this wall. It is assumed that the pressure difference between the two points will induce an airflow and that the discharge equation is still valid. Other studies on single-sided ventilation [iii], indicate that such assumptions often underestimate the driving force which is, in the real situation, much supplemented by turbulence, buoyancy, etc. However those studies were conducted in temperate climates with substantially lower levels of outside temperature, than that experienced in the tropics. In the absence of such studies undertaken on the climate in question, the discharge equation is held valid for differences in pressure coefficients. Experience of occupying rooms with single-sided ventilation in Dhaka substantiates this assumption.

The inlet airspeed has been substituted for the indoor velocities. With very large rooms, this assumption cannot hold, as the turbulence and cross-currents of air flow will modify the resultant air velocity considerably. However, as the size of window opening in houses of Dhaka is typically quite large relative to the floor area of the room, it was considered that the calculated airspeed value at opening would be a reasonably reliable indicator of expected average indoor airspeeds.

Without full-scale tests in the given situation the estimations of natural airflow cannot be verified. This could be a useful topic for further research in this field.

Discussion of the Results

The effect of room orientation on the placement of openings in buildings in Dhaka was found to be significant. Rooms with single-sided ventilation were found to have poor volumetric airflow rates and also extremely low indoor velocities, even when they faced the principle direction – South. The results clearly demonstrate that natural ventilation cannot be relied on to provide thermally comfortable conditions for occupants of rooms with single-sided ventilation, especially during the warm months March to October. The 'comfort status' of such rooms is 'stuffy' all the time. The overall comfort status of the test rooms are indicated in Fig. 3 and Table 5. As indoor airflow from natural means is not adequate for thermal comfort under afternoon conditions, the results clearly indicate that the use of mechanical fans cannot be eradicated in rooms with single-sided ventilation. The effect of this on energy consumption therefore is significant.

Table 5 Overall comfort status of test rooms in percentage of time

Room no	Comfortable	Uncomfortable	Stuffy
1	45.6	7.8	46.6
2	42.9	43.3	13.8
3	13.6	32.9	53.5
4	5.3	5.2	89.5
5	46.8	50.4	2.8
6	2.8	48.4	48.8
7	-	-	100
8	-	-	100
9	-	0.8	99.2
10	-	-	100

Rooms with windows on adjacent walls were found to be far superior to rooms with those with single-sided ventilation, especially so when one of the windows is located on a wall facing South. Such rooms can be comfortable for certain periods even without the use of fans.

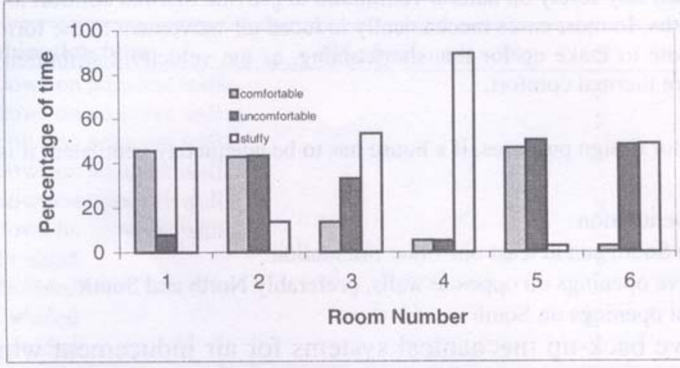

Fig 4 Comfort Status in different rooms of the test house

For the third category, rooms with windows on opposite walls, the results again clearly indicate higher performance when the windows are orientated towards the South and North. These rooms are still unlikely to be comfortable all the time, without the use of any active controls like fans for induced air-movement. Moreover under conditions when natural breeze cannot be relied on to reach the openings in expected force, the situation inside such rooms may be considerably poorer than predicted. Rooms with windows on East and West show lower comfort status, considered from the point of view of ventilation, as the predominant airflow is from the south during the warm period in Dhaka.

From the point of view of energy savings, cross-ventilation can be a bonus, especially when this is provided by openings on adjacent walls. When conditions around the site are unfavourable for wind flow, only then will the need for mechanical inducement of wind flow arise in rooms with adjacent inlet-outlet combination. This clearly points to the need for architects to carefully work out living spaces with adequate cross ventilation at the design stage. The potential for energy savings cannot be ignored considering the national need for energy budgeting that is becoming imperative in recent years.

In general, in the urban scene, it is difficult to find sites with unlimited airflow. With increasing pressure from developers and clients alike to build on as much of the site area as possible to maximise profit, cross ventilation itself is becoming a luxury. However, the attempt should be made to provide openings on at least two walls of each habitable room from the consideration of energy savings. For rooms placed on the side of buildings, this is not difficult to achieve. But for rooms with only one external wall, the provision of more than one opening is something of a challenge. The results of this experiment show that providing two openings on the same wall does little to alleviate the stuffy conditions felt in these spaces. A possibility is to provide high windows towards the interior of the buildings so that air can flow in through the windward opening and pass into the interior of the building by the high windows, before exiting through leeward openings on the opposite side of the building. In such cases though, there may be some decrease of sound privacy at the cost of increased thermal comfort. Architecture in general needs to face these compromises and architects require to be aware of the available options to suit the comfort situation.

Conclusions

This investigation aimed to study a specific test house in a representative Dhaka urban setting, for wind climate typical for the region, and from the results establish general observations regarding interior airflow and scope for thermal comfort within spaces. Airspeed needed for thermal comfort under 3 pm conditions (considered in Dhaka to be the day's worst thermal situation) of each month of the hot/warm seasons were evaluated and compared to the results of the experiment on the test house. From the comparison the 'comfort status' of the test rooms with different ventilation characteristics were determined.

The study of the combined effects of air-movement, temperature and humidity in Dhaka revealed that none of the rooms of the test house can rely solely on natural ventilation to provide thermal comfort air-movement during the afternoons of warm months. In most cases mechanically induced air-movement in the form of ceiling or pedestal fans will be quite adequate to make up for this shortcoming, as the velocity distribution around fans is higher than that needed to restore thermal comfort.

This study revealed that for design purposes, if a house has to be adequately ventilated, it is important to:

- Avoid single-sided ventilation
- Provide openings on South and at least one other orientation
- When possible to have openings on opposite walls, preferably North and South
- Avoid rooms without openings on South
- provide alternative back-up mechanical systems for air inducement which will take care of times when natural wind velocity cannot guarantee thermal comfort airspeed in the interior.

Buildings that are designed considering climatic aspects, will have the potential to save on energy, as passive means are given priority. This paper demonstrates that orientation of rooms and hence layout of functional spaces has to be proper if energy savings are to be achieved.

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