THERMAL COMFORT AT PEDESTRIAN LEVELS IN A LARGE MULTI-STOREY DEVELOPMENT IN MARITIME TROPICAL CLIMATE

M B Ullah
Associate professor*, Department of Building, National univesity of singapore
*Present address: Independent Consulting Engineer, 1 Hudson Court, Maritime Quay
London E14 3QH, U.K. (e-mail:barkat46@hotmail.com)

ABSTRACT

While a lot of attention has been given in the study of indoor air distribution and its thermal performance, buildings clustered together in a development modify the outdoor environment to a great extent and the outdoor thermal performance of such a development is a critical factor for its success as to its acceptance by the tenants and visitors and their enjoyment of the outdoor activities. In such a development, careless design may lead to areas of stagnant or little air movements, which may lead to a very uncomfortable condition for even a few minutes of walk in a tropical maritime climate which has a predominantly humid and hot weather. A study was carried out to assess and predict the outdoor environment at a proposed development to contain seven multi-storied buildings in Singapore. The pedestrian level airflows were determined using a Computational Fluid Dynamics software for various predominant wind velocities and directions. At certain locations in the developments, outdoor sedentary activities, such as outdoor restaurants were considered. For such places, the local air velocities can be combined with the relative humidities and dry bulb air temperatures to calculate the Predicted Mean Vote (PMV) to predict the thermal comfort levels, assuming that the space is shaded from the direct sun. The other physical parameter in the comfort equation is the mean radiant temperatures. While it is possible to simulate the surface temperatures by considering the solar geometry and a database of solar radiations, the present study concentrated on the CFD simulations and the mean radiant temperatures were assumed to be 2 degrees above the dry bulb air temperatures. This assumption is based on a thermogarpic study of building surfaces under shades, in which the surface temperatures were found to be about 2 degrees above the air temperatures for over a large percent of time. In warm and humid climatic areas, air movements are very welcome as it can remove the sweatings by convection and evaporation. The original development plan showed pockets of stagnated air, which are very uncomfortable. With help of CFD simulations, modifications were suggested for the building designs to offer more airy environments around the buildings. The solution opened up the possibilities of enjoying the outdoor green environment and leisurely pastimes by the owners, tenants and visiting public to the development.

INTRODUCTION

The tropical maritime climatic zone expands around the equatorial belt of the earth and is characterized by its lush green landscape. This climate also suffers from a moderately high dry bulb air temperature and relative humidity as well as high solar insolation. The mean radiant temperatures are also higher than the air temperatures for most of the times. This leaves the fourth physical parameter of the comfort equation, namely, the air velocity to be only means to alleviate the thermally uncomfortable condition.

The frequencies of winds on the four vertical directions, and their mean speeds were studied at Department of Building, National University of Singapore. The weekly wind frequencies and the mean speeds for the four orientations are given in Figures 1 and 2.

It is observed in Figure 1 that the predominant direction of the wind is from the North; the wind speed is also substantially higher when compared to those from the other directions. The speed is found to vary between 1 m/s to 2.5 m/s for the north direction; the frequency was found to be 95% in a particular week; the lowest frequency was 32%.

For modifying the micro-climate of the open space for thermal comfort, water sprays may also be considered.

ANNUAL DRY BULB TEMPERATURE AND RELATIVE HUMIDITY DATA BASE

In order to assess state of comfort level and the cooling enhancement that can be produced from the water spray as architectural features, data regarding the dry bulb and wet bulb temperatures of the air are required. At the Department of Building in National University of Singapore, the dry bulb temperature and relative humidity are recorded for a number of years. Wet bulb temperatures can be extracted from the dry bulb temperature and relative humidity. Out of the data, the data for months of April to December in the year of 1999 and for the months of January to March in year of 2000 have been extracted to give us a complete one year's data.

THERMAL COMFORT EQUATION

The comfort equations, basically a set of heat balance equations, were originally proposed by Fanger (1972) and adopted in ASHRAE Standard 55-663(1992). The equations contain six factors, namely, activity level of the person, thermal resistance of the clothing, air temperature, mean radiant temperature, relative air velocity and the water vapour pressure (i.e., air relative humidity). An imbalance in the heat equation gives rise to a thermal load, L. It was established that the thermal sensation can be co-related to the thermal load, L and the activity level, M/A_{Du}, which were empirically related as follows:

$$Y = (0.352e^{-0.042(M/ADu)} + 0.032)L$$

where Y represents the response obtained from subjects who were exposed to different environmental conditions. The value of Y is known as the predicted mean vote (PMV) for a thermal environment for a given clothing and activity level and is considered to be thermally comfortable for a value of +0.5 to -0.5. Thus, the percentage of time, when the PMV falls within this range, provides a good estimate of thermally comfortable environment prevailing at a place.

A point of caution is that, the PMV is for the steady state conditions and can be considered for actitivities, such as outdoor eating in a restaurant. The equation will not be applicable in direct exposures to sun and transient walking from one building to another .

CFD SIMULATIONS

The objective of the computational fluid dynamics (CFD) simulation at the outdoor has been to obtain the air velocity field data at the built-up pedestrian level places. This information helps the designer to plan for open-air activities.

The CFD simulation tool has been found to be a cost-effective way of obtaining the information regarding the velocity fields around the building and in the critical areas. In this present study, we carried out simulations for the predominant wind direction, which was found to be from the North. A factor, which we term to be 'Built-up Factor(BF)', was determined with respect to a free field velocity of 1 m/s at a height of 10m. At lower levels, the log law, given below, was used to get the free field velocities:

$$u= u_o \log_e(z/z_0).$$

These velocities were used for the free field boundary condition, and CFD simulations were carried for the development. Once a converged CFD solution is obtained, the ratio of a local velocity to the free field velocity at the reference height (10m) was found to give the built-up factor. For pedestrian level, the local velocities were found at a level at 1.2m from the ground. CFD simulation runs with a different free field showed that the built-up factor remains constant.

However, the built-up factor is location dependent. We have chosen three locations, in which we have interests in the current study: one at the space south of Building A, which looks over a park and is considered for open air restaurants; this location is marked as Pt A in Figure 4. The second location is the space between Buildings B and D, marked as Pt B and the third place, Pt C is in the space between Buildings D and E as shown in Figure 4 respectively. At Point C, a light railway train station was considered to be built; this space will be covered by two canopies at a height of 16m and 18 m above the ground.

The various CFD simulations made are listed below:

1 Base case with the North wind, without any opening in the buildings; the CFD simulated velocity vectors at 1.2m height from the ground are given in Figure 5.
2. A case with the North wind, with a straight 20m wide and 9m high opening (concourse) in the middle of Building A; the CFD simulated velocity vectors at 1.2m height from the ground are given in Figure 6.
3. A case with the North wind, with one 10m wide and 9m high straight opening (concourse) in the middle of Building B; the CFD simulated velocity vectors at 1.2m height from the ground are given in Figure 7.
4. A case with the North wind, with two straight openings, one 10m wide and 9m high straight opening (concourse) in the middle of Building A and another 20m

wide and 9m high opening (concourse) in the middle of Building B; the CFD simulated velocity vectors at 1.2m height from the ground are given in Figure 8.

5. A case with the North wind, with two openings: one bell shaped opening with widths of 12m at both ends and tapering to 8m at the middle in the middle of Building A and another 14m wide L-shaped opening at the middle of building B; both the openings are 9m high; the CFD simulated velocity vectors at 1.2m height from the ground are given in Figure 9. The special shapes attempted to catch and channel the wind to stagnant areas, providing greater airy and thermally comfortable environment.

STUDIES OF THERMAL ENVIRONMENTS

In Table 1 are given the values of BF for the North wind for 5 building configurations, described above. For these places, the PMV's were also found using local velocities and climatic variables such as the dry bulb air temperatures and relative humidity. These places are assumed to have mean radiant temperatures 2 degrees above the dry bulb temperatures and under shades. The subjects are wearing light clothes.

In figure 10 are compared the effects of using openings in the two buildings A and B to alleviate the stagnations at Pt A and B.

Providing openings in these two buildings facilitate the natural flow of wind from the North and the best configuration is found to be for Case 5, in which the natural flow is best achieved. The bell shape works as a wind catcher and the other end distributes the air over a larger space at the South side of Building A, where open air restaurants are considered. The configuration releases a kind of bio-energy, flowing smoothly from the North through the complex and removing major stagnant areas. The finding is also in common with the ancient Chinese practice of Feng Sui.

WATER FEATURES

A configuration, integrated with water features: two water ponds are proposed to be built. One at the North and the other at the South, interconnected through a network of canals. At the space south of Building A, cantilevered platform can be placed over the water canal. The water level in the pond at the South will be at a lower level than that in the pond in the North and pumps will push the water up from the South. The water from the North will flow down to the pond in the South by natural gravity, proving with the smooth and pleasing sound of naturally flowing water.

MECHANICAL SOLUTIONS

If economic consideration makes the openings at the rentable lower floors unacceptable, then the following mechanical solutions may be considered:

For position Pt A, fans may be placed on the South wall of PR A building at 2.8m height; the air may be blown through pipes or ducts, kept submerged in water stored in tanks in the car park below for obtaining some cooling of supplied air. Water in the tank will be cooled using cooling towers.

Also, at the evening times, water mists can be sprayed at this area.

Position B, though suffers from some stagnation, it is a transitional space, through which people will walk by. During rush hours, the fans and the spraying of water mist can also be considered for this space. However, the condition here is not as critical as that of position A.

WATER SPRAY

Water and water mists sprayed in the air can reduce the dry bulb temperature of the air by a process of direct evaporative cooling. The wet bulb temperature of the air limits the temperature to which the air can be cooled.

The process of direct evaporative cooling is adiabatic in nature. Heat is required to be added to evaporate the water. It is supplied by the air, into which the water is sprayed. This results in the lowering of the dry bulb temperature of the air. The initial and the final conditions of the air fall on a line of constant total heat (enthalpy), which nearly coincides with the line of constant wet bulb temperature.

The maximum reduction in dry bulb temperature is the difference between the dry bulb and the wet bulb air temperatures. If the air is cooled to the wet bulb temperature, it becomes saturated and the process will be 100% effective. The effectiveness is defined as the percentage depression of the dry bulb temperature divided by the difference between the dry bulb and wet bulb temperatures of the air. In this study, the water sprayed into the air is assumed to cool the air at an effectiveness of 60 percent (ASHRAE Handbook Applications 1999). The final condition is determined by considering the psychrometric equations given in ARHRAE Handbook Fundamentals, 1997. The results of the thermal comfort analysis are presented in Figure 11. In this figure, two graphs are given: the reference graph represents the percentage of time for which thermal comfort can be expected at various velocities without any comfort enhancing feature; the second curve represents the same with the water spray or atomized water introduced as a mist into the space. Use of fan can increase the air speed and may be considered for enhancing the thermal comfort in space south of Building A. It is noted that the increasing the air velocities above 2.5 m/s does not increase the percentage of comfortable time significantly.

LIMITATIONS

The complexity of the project required that rational assumptions are made for some parameters, or the simulation becomes unmanageable. The general purpose CFD software, called PHOENICS, was found very powerful for predicting the air flows, but it was not an energy simulation package and did not render itself readily for solar simulations and we assumed a mean radiant temperature to be 2 degrees above the dry bulb air temperature. This assumption is applicable in general, if the building surfaces are under shades. We also did not consider the thermal storage effect of the structures, again to keep the simulation to a manageable level. These limitations identify the fact that the findings in this study must not be generalized.

CONCLUSION

In this study, Computational Fluid Dynamics simulations of a building complex have been performed. Three critical locations were identified. The velocities at these locations were correlated to the free field velocities through ‘Built-up Factors’ (BF), obtained from CFD simulations. The free field velocities, recorded in a database, are multiplied by the BF to predict the air velocities at these three locations. This enabled us to estimate the long-term percentage of time, during which these spaces will be within the limiting values of PMV for thermal comfort, if the assumed conditions are met, i.e., there is no direct sun, the activities renders to a steady state (long-term exposure) and the mean radiant temperatures are 2 degrees above the air temperatures.

From the simulations done with the basic configuration, it was apparent that, in the base case study, the space south of building A and the space between Buildings B and D suffer from stagnated air, when the predominant wind direction was considered. Using the CFD simulation, it was possible to find a means to enhance the air movements by placing openings in the middle of Buildings A and B. Finally, a solution with two openings, one shaped like a bell in building A and another L-shaped in Building B, together with integrated water features was suggested.

However, if these openings are found to be economically unviable, mechanical solution should be adopted to enhance the air speeds at these two critical areas, namely, the space south of Building A and the space between Buildings B and D. The air speeds can be increased with fans, placed on the walls and water mists and water spray may be introduced to reduce the dry bulb air temperatures so that the comfort levels there can be enhanced.

REFERENCES

ASHRAE Standards 55-81 (1992) Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating Engineers,Inc.,Atlanta, USA.

Fanger, P.O. (1972) Thermal Comfort, McGraw-Hill, New York.

International Standard Organisation (1994) Moderate Thermal Environments – Dtermination of the PMV and PPD indices and specification of condition for thermal comfort, Geneva, Switzerland.

ASHRAE Handbook Fundamentals (1997), American Society of Heating, Refrigerating Engineers, Inc., Atlanta, USA.

ASHRAE Handbook HVAC Applications (1999), American Society of Heating, Refrigerating Engineers, Inc., Atlanta, USA.

Table I
Built-up factors and % of comfortable time.

Type of configuration	Built-up(BF) factor at positions			(%) of comfortable time at positions		
	A	B	C	A	B	C
Base–No Opening	0.1	0.1	0.67	4.76	4.76	23.2
Straight opening at Bldg B.	0.1	0.4	0.67	4.76	18.07	23.2
Straight pening at Bldg A.	0.2	0.23	0.67	8.62	11.63	23.2
St Openings at Bldg A and B	0.4	0.6	0.67	18.1	22.07	23.2
Bell-shaped Opening at A and L-shaped Opening at B	0.8	0.6	0.67	25.2	22.07	23.2

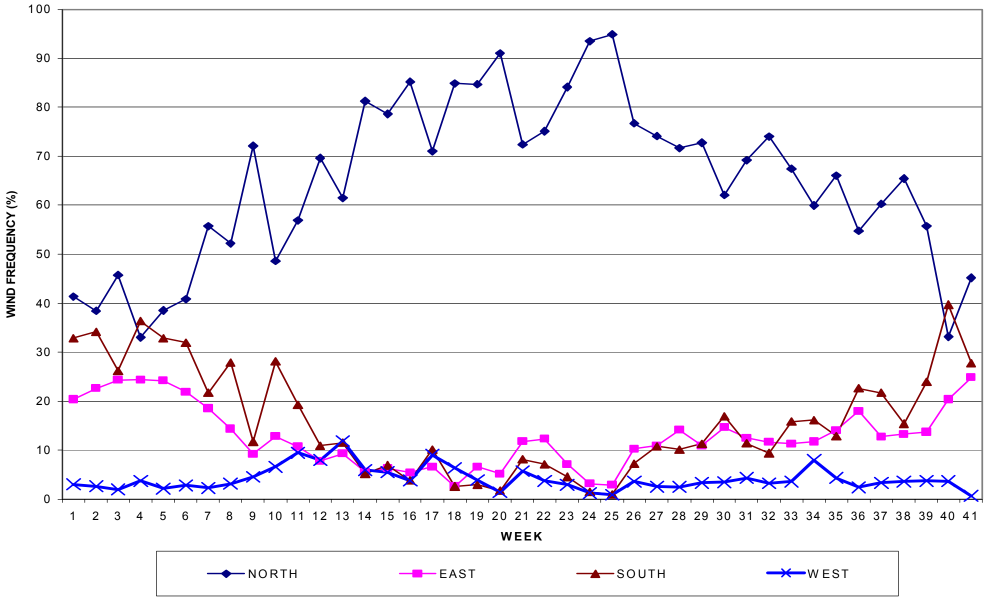

Fig 1Weekly wind frequency for various orientations

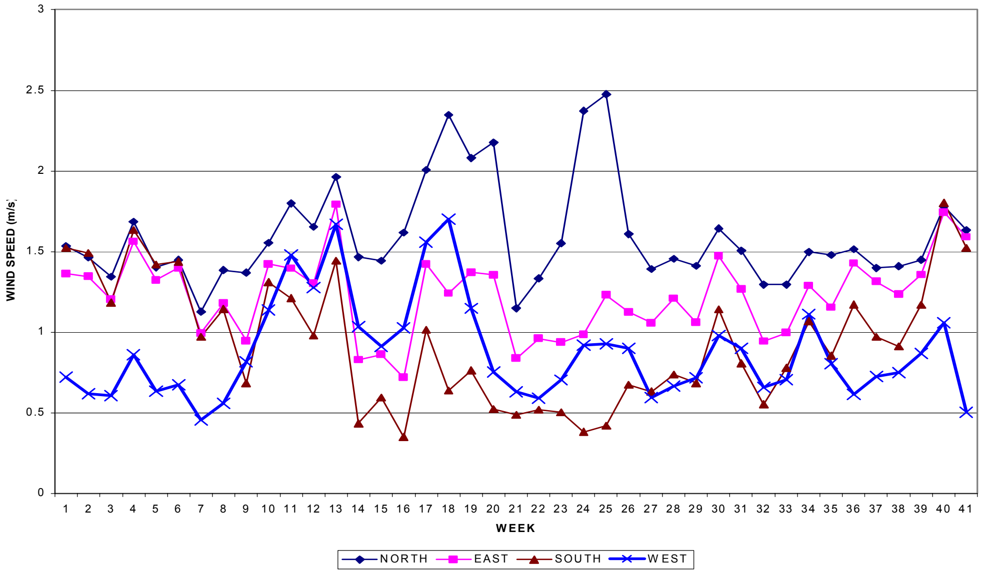

Fig 2 Weekly wind speeds for various orientations

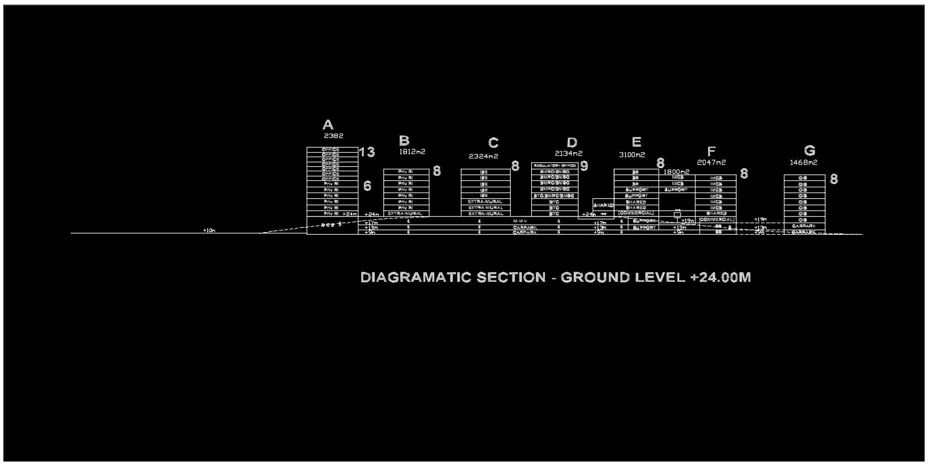

Fig. 3 The Diagrametric section of the seven building Blocks.

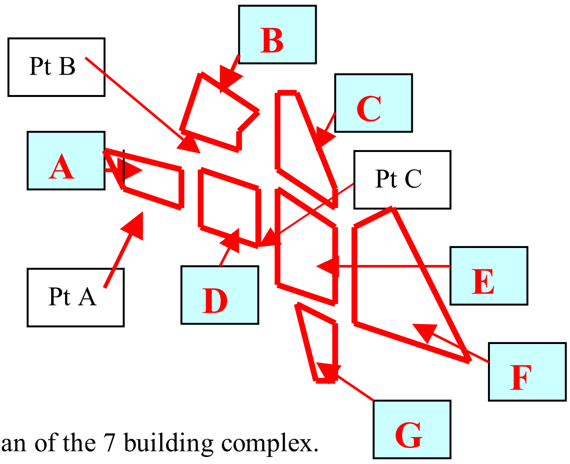

Fig. 4 The Plan of the 7 building complex.

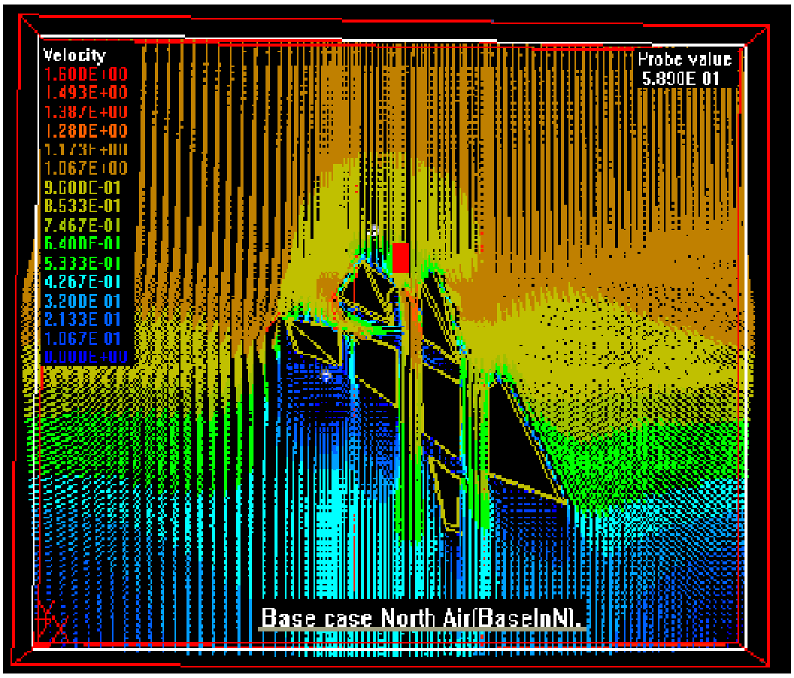

Fig. 5 The velocity profiles for the base case design.

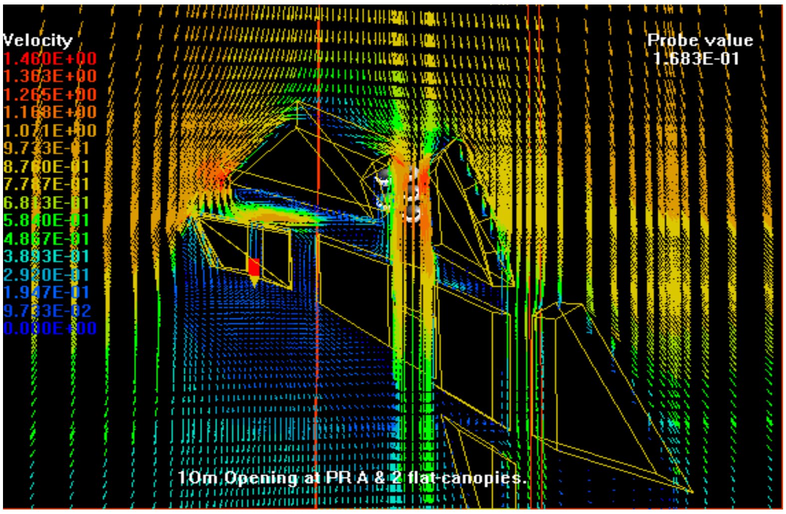

Fig. 6 The velocity field with a straight opening at the middle of Building A (PR A).

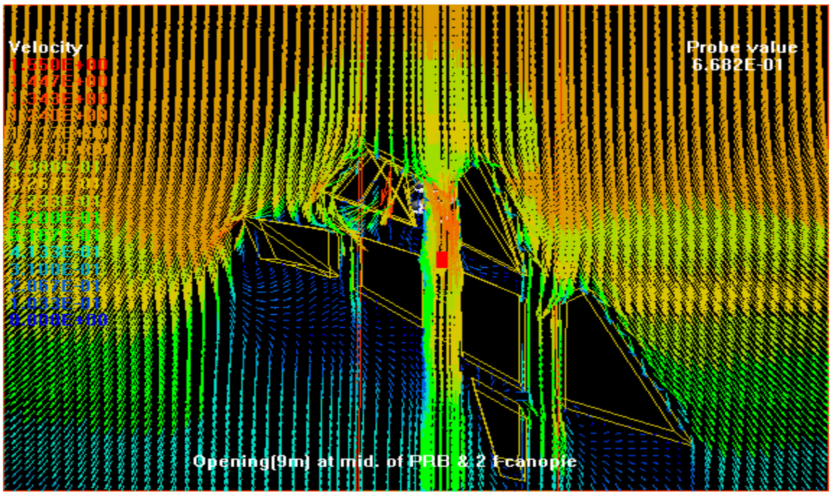

Fig. 7 The velocity field with a straight opening at the middle of Building B (PR B).

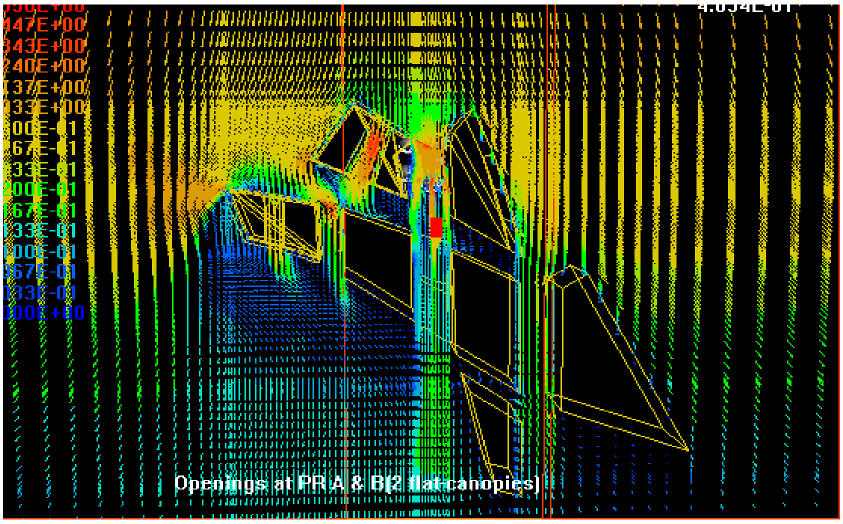

Fig. 8 The velocity field with two straight openings at the middle of Building A and B (PR A and PR B).

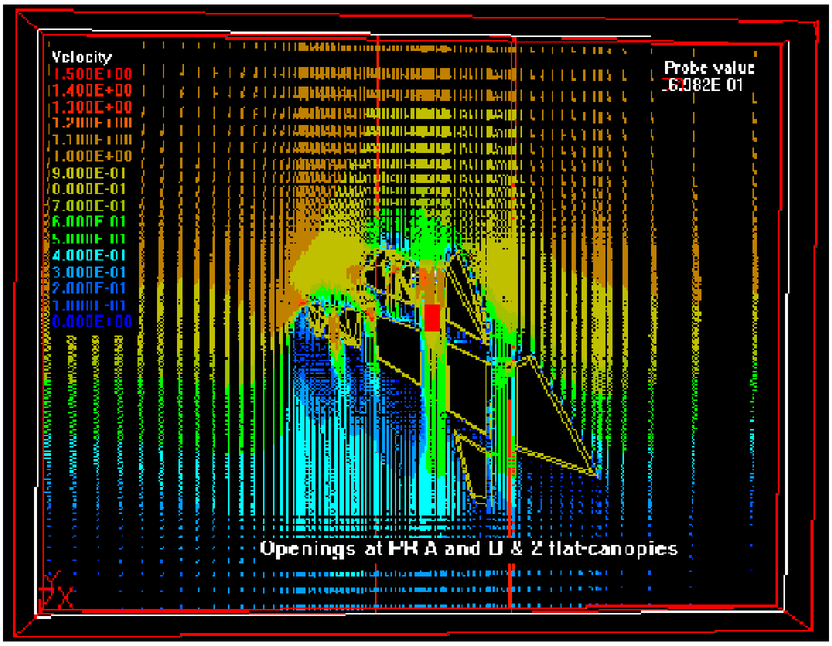

Fig. 9 The velocity field with bell-shaped openings at Building A and L-shaped opening at Building B.

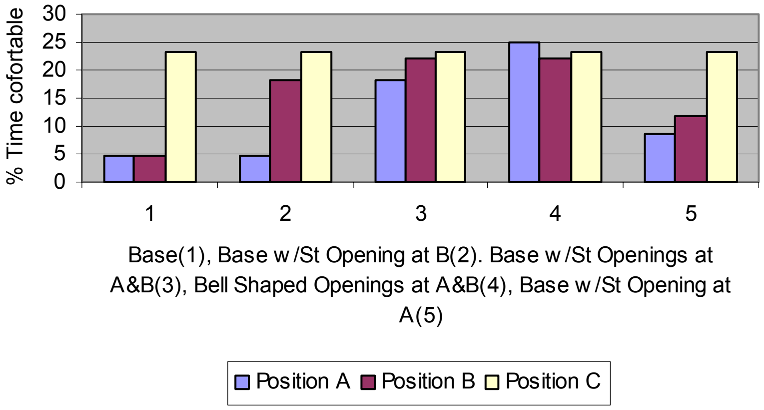

Fig 10 Comparison of comfort conditions with the 5 cases for North Wind for PMV -0.5 to +0.5.

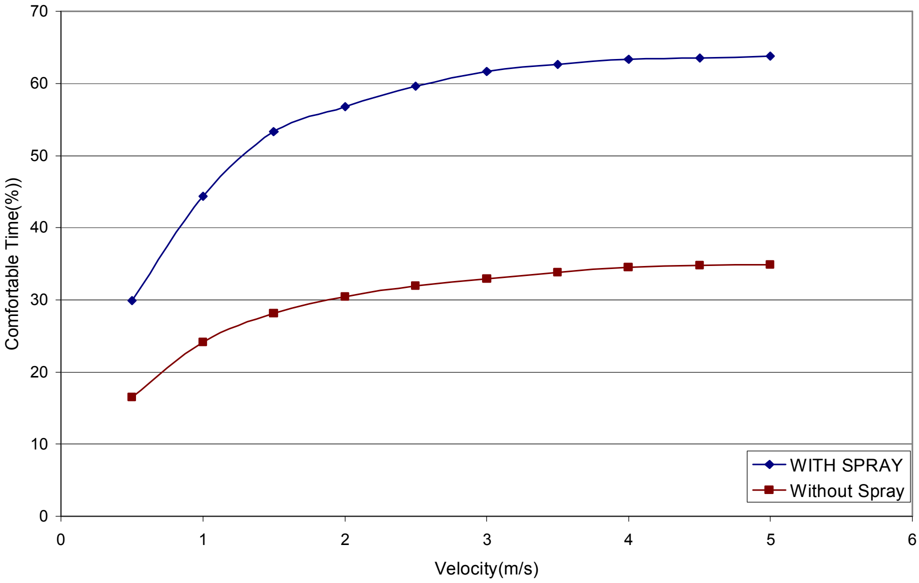

Fig.11 Enhancement of comfort condition with water spray.