Effectiveness of Natural Ventilation in Tall Residential Building in Tropical Climate - A critical analysis & Design Review

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ABSTRACT: Natural Ventilation exploits where natural forces of wind and buoyancy to supply fresh air for physiological purposes and sometimes for cooling. There is a lack of rigorous studies on implications of more intuitive approach towards passive cooling technique in tall residential building in tropical climate. The situation is more vulnerable in the case of tall buildings as people are getting more affluent and air conditioning is becoming more popular to achieve desired thermal comfort. Moreover, natural ventilation in tall building to achieve acceptable thermal comfort and low energy consumption is not an easy task. However, the interconnectedness of various design issues is addressed at one time rather individually to achieve wind induced natural ventilation in buildings. Since wind-driven natural ventilation works best in tropical climate, in this paper, the study is carried out by analysing relevant case studies. In addition, the effectiveness of natural ventilation performance is interpreted in relation to various survey and test results and adaptive thermal comfort theory using "Building bioclimatic Chart" for developing and developed countries. The aim is to analyze the climate interactive design based on natural ventilation performance in different tropical cities and cultural context by taking Kanchanjunga apartment, Mumbai, MBF Tower, Penang and 1 Moulmein Rise, Singapore as case studies. ***Using simulation based programs like CFD and TAS, it is found that the residents are naturally acclimatized to the local climate conditions*** *and the effectiveness of natural ventilation in tall building is not merely dependent on wind force but also the strong correlation between the thermal comfort perception and wind sensation. Furthermore, this paper also concludes with a conceptual tall residential building by mapping solar radiation and wind speed on facades, that can rely on wind induced natural ventilation in tropical climate.*

Keywords: Natural Ventilation; wind and buoyancy; Building bioclimatic Chart; thermal comfort; solar radiation and wind mapping

INTRODUCTION

Globally 15% of all electricity consumption is due to air conditioning & refrigeration and this percentage is growing rapidly. Air conditioning systems are the main consumer of energy in tropical climates. The use of air conditioning is so pervasive that it has resulted in drastic increment of electricity consumption by building industry. The move towards air conditioning is particularly prevalent in the case of tall buildings as people are getting more affluent; air conditioning is becoming more popular to achieve desired thermal comfort. Studies have shown the percentage of households in Singapore who are using air conditioning has increased significantly in the past 20 years from only 7.8% in 1978 to 57.7% in 1998.

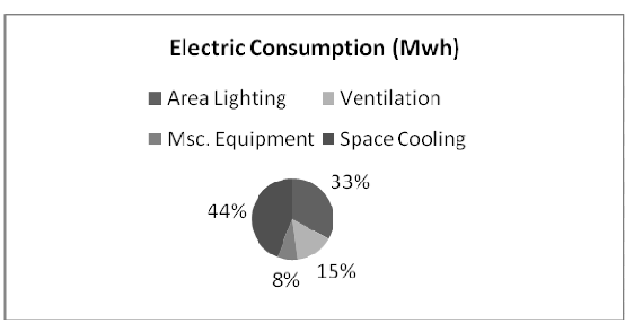

Figure 1: Annual energy consumption by end user in the tropics, Source: Nyuk Hien Wong, 2009

Although the concept of natural ventilation is not complicated, it is a challenge to design naturally ventilated buildings since it is difficult to control. Natural ventilation is the intentional flow of outdoor air through an enclosure under the influence of wind and thermal pressure through controllable openings. The arrangement, location and control of ventilation openings combine the driving forces of wind and temperature to achieve desired ventilation rate and good distribution of fresh air in the building.

EFFECTIVENESS OF NATURAL VENTILATION

"As the location is the most endemic factor, climate provides the designer with a legitimate starting point for architectural expression in the endeavors to design in relation to place, because climate is one of the dominant determinants of the local inhabitant's lifestyle and the landscapes ecology" (Yeang, 1996). Ventilation is the most effective and simplest method to provide indoor thermal comfort, even in most hot climates for some specific period when the natural ventilation could be a favorable option to achieve thermal comfort, however in warm-humid climates natural ventilation can be an effective cooling strategy year round. (Givoni, 1997)

NATURAL VENTILATION PRINCIPLES

Location of openings for ventilation and the shape of the building together act as controller for natural ventilation and it can be differentiated by three different principles:

- Single-sided ventilation

- Cross ventilation: Cross ventilation with 2 side openings, The Wind wing-wall, Cross ventilation with Central Atrium, Cross ventilation with Perimeter Conservatories.
- Stack ventilation

ADAPTIVE THERMAL COMFORT IN TROPICS & THE BUILDING BIOCLIMATIC CHART

Equatorial climate is spread on either side of the equator along a thin strip of up to 10 to 15 degree on either side of the equator according to building design aspect, which is warm all year round, and the other is regions with hot humid summers with cool and cold winter going into Africa and South America. It is characterized by high temperature and relative constancy of the annual average temperature and humidity with little variation in diurnal temperature range i.e. about 8^0C. and minimal average monthly temperature i.e. at the range of 1 to 3 ^{0}C. The

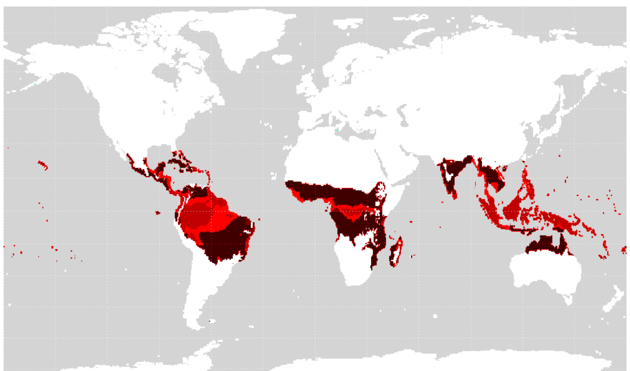

Figure 2: world map with Tropical region

annual mean temperature is 27^0C and Maximum temperatures range is around 32^0C and it can reach to an extreme of 38^0C with relative humidity around 90% and rainfalls occurring mostly in the afternoons. Though the regions of the tropics have similar temperature, rainfall and humidity conditions, the local climate has a great impact on building design alike their wind condition may vary from one place to another. In coastal areas, regular land and sea breezes are created by the constant heating and cooling patterns of land and sea respectively providing regular wind flow mainly during the afternoon time with windless night. Up to about 25°c and between 30 to 80% relative humidity, a sedentary body cannot experience any difference in thermal sensation, skin wetness, body temperature and sweat rate. Human thermal comfort in terms of physiological parameters (age, sex etc.), external parameters (activity and clothing) and physical parameters (Air temperature, relative humidity, light intensity and air velocity) are the main parameters affecting human thermal comfort. Indeed, thermal comfort expectation is influenced by the degree of adaptive opportunity: as people have more control over the environment in their home as compared to office, they tend to accept warmer environments more readily in their homes than in offices. It can be concluded that that passive design strategies probably have greater potential to provide thermal comfort in hot humid climates than is generally believed. Thus thermal preferences extend to a wider range of airflow speed and temperature. The BBCCs for hot-developing countries offer thermal comfort boundary for two conditions: 'still air' (less than 0.25 m/s), which lies between 18˚C (winter) and 29˚C (summer) and for 'a very light breeze' (2.0 m/s), which extends the limit to 32˚C where as for developed countries the range varies from 18˚C to 25˚C (winter) and 20˚C to 27˚C (summer) in 'still air' and for 'a very light breeze' (2.0 m/s), which extends the limit to 30˚C during summer. The upper (summer time) temperature limits decrease above 50% relative humidity and upper limits are placed on RH of 80% for still air and 90% for a very light breeze. In this paper, This is used to interpret the overall effectiveness of natural ventilation in the selected case study buildings. According to Yeang (1999), direct and indirect physiological effects are the two ways to enhance the level of human comfort in natural ventilation. He termed it as 'Comfort Ventilation', which involves more wind through openings to increase the indoor airflow and this result in the occupants feeling cooler. Direct approach is ventilative cooling & indirect approach is to improve the level of comfort by ventilating the building at night to cool down the interior, which is termed as 'Nocturnal Ventilative Cooling'. Moreover, Givoni (1998) stated the comfort ventilation is applicable mainly to regions and seasons when outdoor maximum air temperature does not exceed 28-32^{0}C with diurnal temperature range less than 10^0C. A physiological cooling effect can be achieved even when the humidity level and indoor air temperatures are high. The rate of evaporation of sweat from skin increases with the increase in velocity of indoor air (1-2 m/sec) and it minimizes the discomfort occupant's feel as compared to when their skin is wet (Yeang, 1999).

VENTILATION REQUIREMENTS

Ventilation serves three distinct functions, such as: Health, thermal comfort and structural cooling ventilation.

Requirement	ach	$ls^{-1}\ m^{-2}$
Health	0.5 to 1	0.4 to 0.8
Comfort	1 to 5	0.8 to 4
Cooling	5 to 30	4 to 25

Figure 3: Required Ventilation rate for different functions

The primary concern is continuous ventilation for comfort requirements and it impacts all aspects of building design. Proper care must be taken in such climates to protect from sun & rain without compromising on ventilation conditions.

PROCESS

Three case studies are analysed to identify effectiveness of natural ventilation in tropical climate. Consequences that related to the generic building type and consequences that are common for all the three generic types are identified with respect to the natural ventilation strategies.

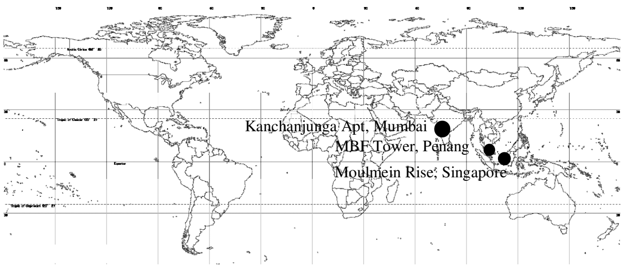

Figure 4: Location map of analyzed buildings

METHODOLOGY

The main objective of this paper is to analyze the efficiency of the natural ventilation and this is undertaken using two different methods: Qualitative that includes a post occupancy evaluation and Quantitative Analysis through TAS and CFD simulation

DETAIL STUDY:

CASE 1 - KANCHENJUNGA APT. , MUMBAI

Charles Correa's 28 storeyed 'Kanchanjunga Apartment' 441 SQ.M of footprint in Mumbai elaborates his penchant for sectional displacement appropriately accompanied by changes in floor surface. Here he pushed his capacity for ingenious cellular planning to the limit. A great combination of interlocking one and a half storey, split-level, 3 and 4 bedroom units with the two and half storey 5 and 6 bedroom units can be seen successfully attempted in a high rise building creating 32 luxurious apartments. The main ideas key features:

- Climate: Tropical wet & Dry
- Site and situation: City landscape surrounded by mid-rise and high-rise structures.
- Prevailing wind direction: From southwest and northwest
- The apartment himself is a direct response to the present society, the escalating urbanization, and the climatic conditions for the region.
- Well ventilated and appear to suit the contemporary life style.
- One and two floor height terrace gardens in each flat alike to the protective verandas in bungalow.
- The typical open floor plans with double heighted living room for cross-ventilation.
- Best views of Arabian Sea on west just 450 m away and the harbour on the east.

The following criteria were used for selection of the rooms to be simulated:

- The highest solar gain receiving rooms are selected. The rooms, which are used most of the time by the occupants.
- To check the variation in airflow rate with respect to height, the living and dining space and North west bed room (receive high solar gain) of ground floor, 12th floor and 24th floor
- To check the variation in airflow rates according to change in orientation, both the living and dining space in each flats on ground floor, 12th floor and 24th floor (since two flats in one floor are facing opposite to each other)
- Southeast bedroom on upper floors such as 1st, 4th, 7th, 10th, 13th, 16th, 19th, 22nd and 25th.

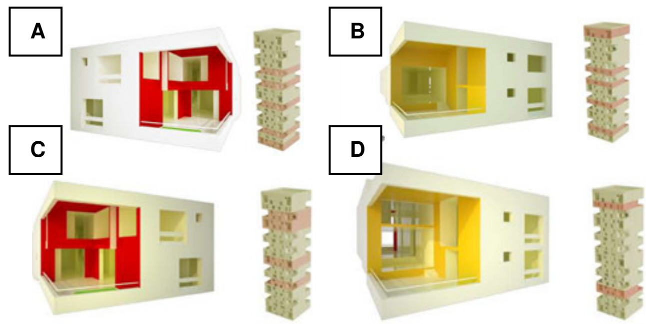

Figure 5: Different Types of flats in Kanchanjunga Apartment Mumbai

Figure 6: View & TAS model of the building

CONSIDERATION DURING SIMULATION

Analysis Period: Average monthly, Summer period : March and April (wind direction from Northwest) & May (wind direction from Northwest and Southwest)

Window to Wall ratio: The living and dining space – 48%, NW bed rm. - 34% & SE Master bed rm. - 45%.

Shading devices: Each openings are well shaded with balcony and terrace gardens.

Building Materials and Construction: As per base condition and earlier study (U value of external facade ranges from 0.3 W/m^2 ^{0}C to 3.6 W/m^2 ^{0}C)

Roof: 150mm Reinforced Cement Concrete (U=7.45 W/m^{2}C), Floor/Ceiling: 150mm R. C. C + tiles (U=3.07 W/m^2 ^{0}C), Additional construction materials, plaster, white paint etc. are also taken in to consideration (refer section 2.7 for detail)

Occupancy pattern, Planning and Program: By interviewing the occupants.

The living and dining space: Occupied period (morning - 7 AM to 10 AM) and evening (6 PM to11 PM)

North West bedroom: Occupied period (11 PM to 07 AM) at nighttime only.

South East Master bed room: Occupied period (11 PM to 07 AM) at night time only

Internal Conditions: As per occupancy

The living and dining space: Three occupants, North West bedroom: one occupant, South East Master bedroom: two occupants

Schedule of opening:

Full day ventilation: Doors and window openings are 50% open 24 hours

Nighttime only ventilation: Doors and window openings are 50% open during nighttime i.e. from evening 6 PM to morning 10 AM

Nighttime only ventilation: Doors and window openings are increased from 50% to 75% open during nighttime i.e. from evening 6 PM to morning 10AM

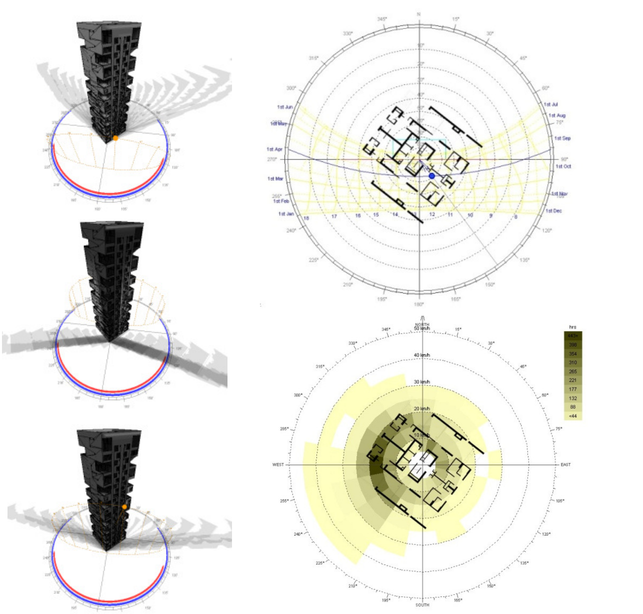

Figure 7: shadow analysis, sun path and yearly prevailing wind (March and April avail northwest prevailing wind whereas May and June avail southwest)

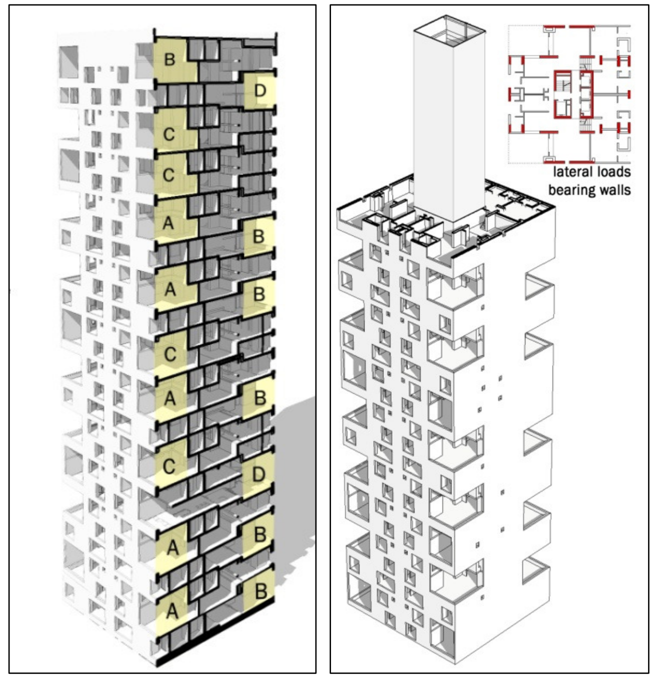

Figure 8: View & TAS model of the building

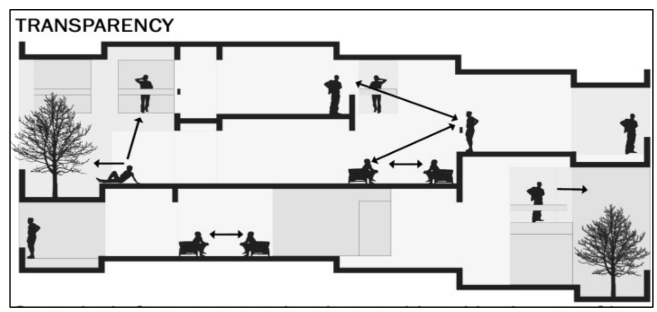

Figure 9: Section through Flat C & B

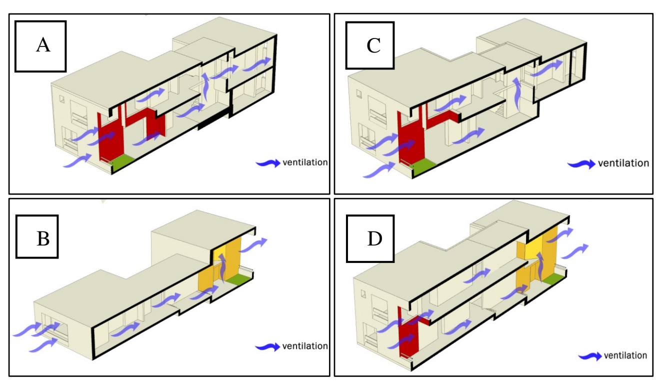

Figure 10: Ventilation strategies for different types of Flats

RANGE OF THERMAL COMFORT

Mean minimum and mean maximum temperature in the Summer: 26.2°C, 33.3 °C °C & Indoor comfort Temperature (Summer): 25 °C - 32 °C, mean minimum and mean maximum temperature in the Winter: 16.3 °C, 26.2 °C & Indoor comfort temperature (winter): 22°C - 27 °C.

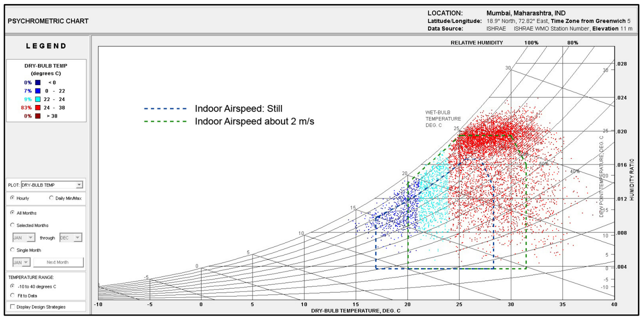

Figure 11: Psychrometric chart showing the boundaries of outdoor temperature and humidity within which the indoor comfort can be achieved, with indoor air speed of 0.25 and 2 m/s for Mumbai

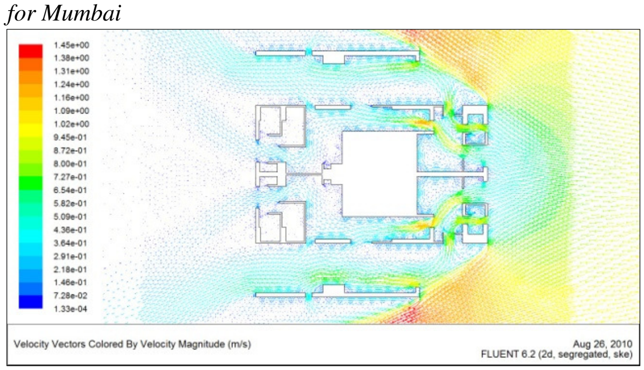

Figure 12: Indoor airflow pattern of Type D

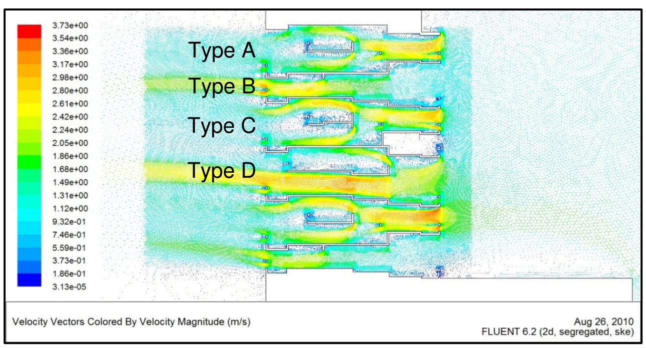

Figure 13: CFD Testing of detail section of tower

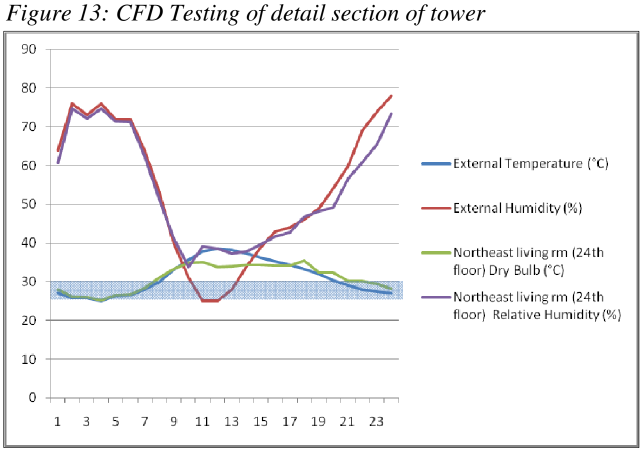

Figure 14: Indoor Temperature variation in hottest day 95

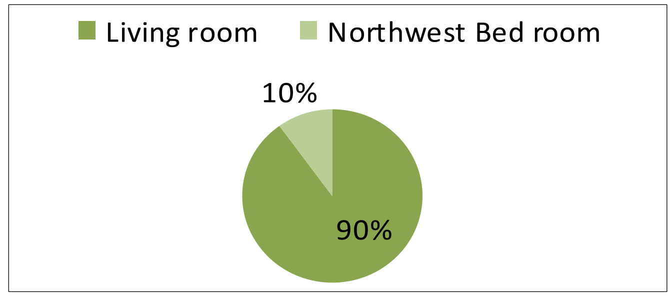

Figure 15: Occupant's survey Results: The most comfortable room during summer

DISCUSSION

Achieved ACH^{-1} :Required 9.4 & Achieved 14.6 for lower floors and 11 for upper floors of type D

Ventilation strategy: Night ventilation works better than 24hr ventilation on the hottest day.

Achieved indoor temperature and ACH^{-1}: Indoor temperature during day time is more than 32^{0}c and during night time below 30^{0}c with in comfort range, Achieved ACH^{-1} varies from 4 to 16 in whole day.

CASE 2 - MBF TOWER, PENANG

The predominant and potential for openness and separation in design of the tower has resulted the architect's idea of "places in the sky" and direct expressive idea of the principle of natural ventilation and vertical landscaping.

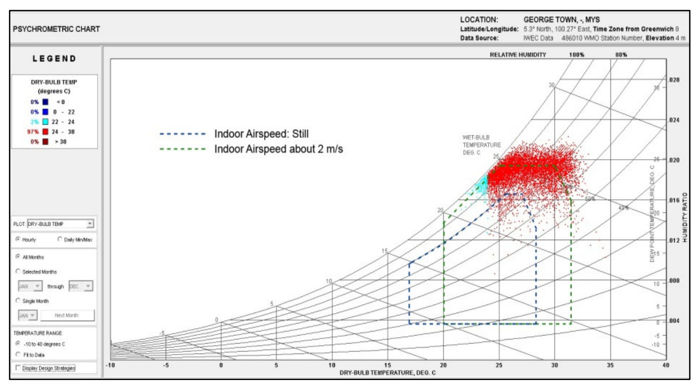

Figure 16: Psychrometric chart for Penang

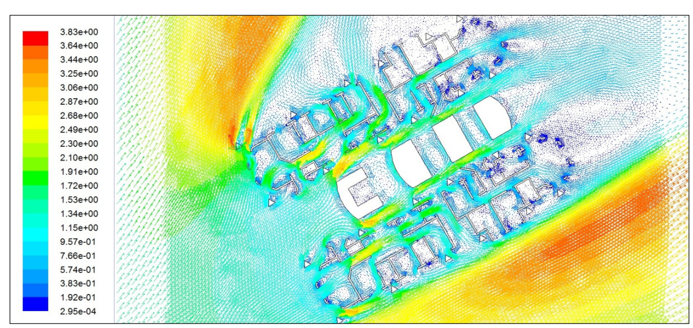

Figure 17: Indoor airflow pattern of Typical floor

DISCUSSION

The building's natural ventilation strategy is generally successful in relation to its form, orientation and the prevailing wind directions. The double storey sky courts at three levels enhance the indoor airflow rate. The orientation of the tower enhance the effectiveness of wind induced cross ventilation during both southwest and northeast prevailing wind as the tower is having openings towards the prevailing wind direction. When the wind changes direction from northeast to southwest for example, wind would still hit the southwestern building blocks at an oblique angle of 75^{o}, hence ensuring the effectiveness of wind driven ventilation.

CASE 3 – 1 MOULMEIN RISE, SINGAPORE

Its varied yet simple façade incorporates features from vernacular housing of Indonesia. The award-winning tower is not only planned to suit its naturally sloping site but all of its facades are also designed according to the direction they face. This holistic approach in planning, smart and innovative details is what makes this aesthetically pleasing building a model for the future residential projects in the city.

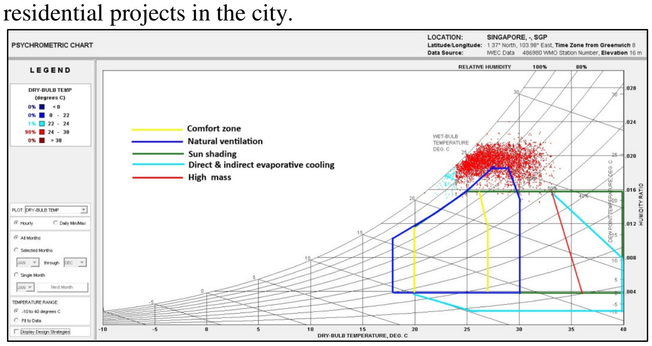

Figure 18: Psychrometric chart for Singapore

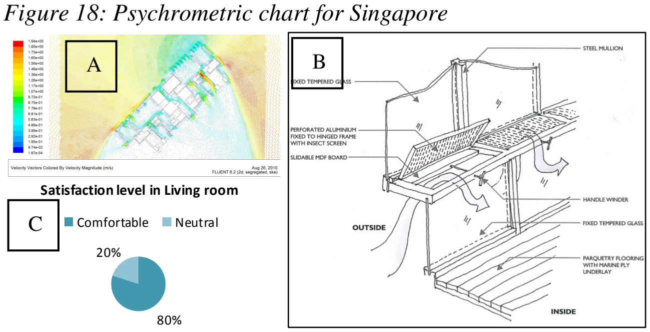

Figure 19: A: Indoor airflow pattern of typical floor, B: Monsoon window, C: Occupant's survey result

DISCUSSION

Variable openings in the façade help the occupants to control their indoor environment as per their requirement. The horizontal "monsoon window" designed by taking inspiration from vernacular design ideas keeps the rain out, while allowing continuous cool breeze in to the indoor space. The choice of materials used in the tower is equally smart especially the perforated sunscreen, which allows indoor airflow by keeping the rain out. Ventilation strategy: 24-hour ventilation works best.

CONCLUSION

- Findings show **evidence that occupants are naturally acclimatized to the local hot and humid climate conditions.** The high usage of air-conditioning for night hours is observed and It indicates that the differences in the thermal comfort perceptions between types and floor levels are minimal.
- This adaptive behaviour contributes in a positive way to the higher-level satisfaction over the environment. When the thermal acceptability is low in the afternoon session, the action of opening the window and switching on the fan reach the highest frequency of choice. However, during night-time, which has a higher thermal acceptability, usage of AC shows a higher frequency.
- Satisfactory ventilation can be achieved with wind incident to the wall at up to an angle of 45° to possible range of 90° & smaller inlet in the windward side and larger outlet in the leeward side.

The indoor temperature can be reduced as low as 5° C at an indoor air velocity of 1 to 2 m/sec. Moreover, the provision should be made to get indoor air velocity of up to 2m/sec to achieve thermal comfort
- 'wing-wall' device and monsoon window could be regarded as some of suitable characteristic design elements to enhance the effectiveness of natural ventilation.

Although the concept of natural ventilation is not complicated, it is a challenge to design naturally ventilated buildings since it is difficult to control.
- Therefore thermal discomfort results from the combination of heat sensation and sensible perspiration hence the higher indoor air velocity would be an effective solution especially when the air temperature is below 33°c.
- Design factors affecting natural ventilation: Built form and orientation, Window opening orientation with respect to prevailing wind, Window size & Sub-division of the internal space

Effect of cross-ventilation on indoor average air velocity (% of external air velocity)

Cross ventilation	Location of openings	Direction of wind	**Total width of openings 2/3 of wall &** Av.	Max.	**3/3 of wall** A v.	**Max.**
Provided	Two openings in adjacent walls	perpendicular	45	68	51	**103**
		Oblique	37	118	40	**110**
	Two openings in opposite walls	perpendicular	35	65	37	**102**
		Oblique	**42**	**83**	**42**	**94**

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