# Assessment of Air Velocity Preferences and Satisfaction for Naturally Ventilated Office Buildings in India


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## ABSTRACT

*Free-running buildings (i.e. naturally ventilated buildings with no mechanical systems for heating or cooling) have the potential to be much more energy efficient than air-conditioned buildings. This paper is based on approximately 3200 instantaneous thermal comfort and 1500 long term background survey datasets from a large scale field study conducted in free-running Indian office buildings. Responses to air movement satisfaction and air movement preference questions, together with concurrent measurements of indoor environmental parameters of air and globe temperature, relative humidity and air velocity are used for this study. The paper gives an insight into the operation of ceiling fans and windows, and the range of air velocity experienced by office workers in free-running office buildings. It gives the relationship between measured indoor air velocity, concurrent air and globe temperature and relative humidity. Instantaneous responses are correlated with the on-site observations on window and ceiling fan operation, as well as indoor environmental measurements. The assessment of preferred air velocity from ceiling fans and operable windows as an adaptive measure in this paper contributes to the development of better designed free-running office buildings in India.*


## INTRODUCTION

India is a rapidly growing economy with a population of more than 1.2 billion which marks 17.6% increase in 10 years. According to the Indian Census of 2011, the country has about 46 cities with population of over 1 million (Census Organization of India) and many more cities will join this list in a matter of a few years. People need buildings to live and work. The growth in population, therefore, is linked to the rapid increase in building construction and infrastructure demand. Building construction and operation requires energy, for most part, in the form of electricity. Coal, a non-renewable resource, is the primary source of electricity in the country. To sustain the GDP growth at 7-8% (projected average), energy security must be ensured. On the other hand, global climate change and the environmental degradation points to the need to chart a more responsible growth path. It is clear that in the current scenario of climate change, energy efficiency in buildings is the most important 'energy source' for India.

The primary end use of electricity in buildings is to provide thermal comfort to occupants through air conditioning. It is therefore important to focus on what constitutes thermal comfort for people in buildings. ASHRAE defines it as 'a state of mind that expresses satisfaction with existing environment'. It also precribes standard thermal comfort conditions for air conditioned and free-running buildings (ASHRAE, 2010). In India, the National Building Code (Bureau of Indian Standards, 2005) provides construction guidelines, administrative regulations, development control rules and general building


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requirements related to fire safety, materials, structural design, plumbing and building services. The Energy Conservation Building Code of India (Ministry of Power, 2007) prescribes minimum standards for energy efficiency in buildings, soon to be mandated across the country. None of these codes propose an explicit thermal comfort model for India. Some individual researchers have worked in this area but their work is limited to residential studies in selected regions of the country (Singh, Mahapatra, & Atreya, 2011; Indraganti, 2010). The dearth of extensive field studies to understand thermal comfort in offices across all climate zones of India led to the conception of the India Model for Adaptive Comfort (IMAC) study in 2011 (Manu, Shukla, Rawal, de Dear, & Thomas, 2014 forthcoming). The primary objective of this study was to develop an adaptive thermal comfort model for India.

This paper presents a part of the IMAC study, focusing on the role of air velocity in the thermal comfort sensation of building users. Adjusting local air velocity through the use of ceiling fans and/or windows is one of the most significant behavioral adaptation mechanisms. Studies show that the building occupants use this mechanism in warm or warm-humid conditions to achieve comfort. Nicol (1974) reported a reduction in thermal discomfort at 32-40 ˚C at air velocity >0.25 m/s in regional studies in India and Iran, supplemented by similar findings from Sharma and Ali (1986). Field studies in the sub-tropical climate of Hong Kong indicate that air velocity of 1.0-1.5 m/s would likely satisfy 80% of the occupants thermally in summer season and that with 1.5 m/s air velocity, the upper limit of comfort temperature reached 33.5 ˚C (Cheng & Ng, 2006).

Studies have also indicated the need for increase in air velocity even in air conditioned buildings to offset increase in temperature (Arens, Turner, Zhang, & Paliaga, 2009). Feriadi (Feriadi & Wong, 2004) reports the tendency of the occupants to modify the hot and humid living environment by turning on fans and opening the windows. Field studies in the warm and humid climate of Bangladesh show an increase in comfort temperature with air velocities greater than 0.3 m/s (Mallick, 1996).

## METHODOLOGY

The analysis presented in this paper is based on the data collected over four campaigns of surveys in office buildings in India, spanning a period of one year. These surveys were administered in five Indian cities selected as representative locations for the five climate zones prevalent in India – warm & humid, hot & dry, composite, moderate and cold. In order to document a wide range of indoor environmental conditions, surveys were administered in naturally ventilated, mixed-mode and air conditioned buildings in these five cities during summer, winter and monsoon seasons. The instantaneous thermal comfort surveys (TCS), which were repeated every season, gathered responses related to thermal sensation, preference and acceptability, air movement satisfaction and preference, clothing and activity. These were accompanied by simultaneous measurement of the indoor climatic parameters – air temperature, globe temperature, relative humidity and air velocity. Building Use Studies (BUS) methodology (Building Use Studies Ltd., 2014) was also used as a post-occupancy evaluation tool to gather long-term responses (Leaman, 1995). It has questions framed to draw responses to the workspace environment on a seasonal basis from past experiences of the respondents. The questionnaire covers aspects such as thermal comfort, ventilation, lighting, noise, indoor air quality, personal control. A total of 6330 TCS and 2002 BUS responses were gathered from 16 buildings under the IMAC 2014 project. Of these, 2005 TCS and 652 BUS responses are from occupants in buildings that were naturally ventilated throughout the year and constitute the data set analyzed in this paper.

In the IMAC study, buildings that did not have any mechanical cooling or air-conditioning systems installed and had ceiling fans and operable windows, were classified as pure naturally ventilated (NV) buildings. Survey responses from NV buildings have been separated from those of the mixed-mode buildings working in naturally ventilated mode at the time of the survey ($NV_{mm}$). Even though the indoor conditions follow the outdoor in both NV and $NV_{mm}$, the premise for this distinction is that subjects in $NV_{mm}$ mode experience AC (air conditioned mode) for a part of the year and, therefore, may have different responses to, and expectations from, the thermal environment of the work space, as compared to those who never experience AC at work. This classification was done during the analysis of the study and it was found that none of the buildings in the composite climate zone could be categorized as NV.

The present paper focuses on the seven NV buildings, one each in the hot and dry zone (HD1) and warm and humid (WH1), two in moderate (MD1, 2), and three in cold (CD1-3) climate zone (Table 1).

**Table 1 Survey schedule and number of responses**

| **Building** | | **TCS** Summer responses (Month) | **TCS** Monsoon responses (Month) | **TCS** Winter responses (Month) | **BUS responses (Month)** |
|---|---|---|---|---|---|
| HD1 | Ahmedabad | 137 (May) | 121 (Jul) | 167 (Jan) | 123 (Jul) |
| MD1 | Bangalore | 38 (May) | 48 (Aug) | 33 (Jan) | 46 (Aug) |
| MD2 | | 132 (May) | 149 (Aug) | 127 (Jan) | 138 (Aug) |
| WH1 | Chennai | 90 (Jun) | 85 (Oct) | 104 (Jan) | 98 (Oct) |
| CD1 | Shimla | 64 (Jun) | 68 (Aug) | 69 (Dec) | 68 (Aug) |
| CD2 | | 120 (Jun) | 126 (Aug) | 111 (Dec) | 108 (Aug) |
| CD3 | | 83 (Jun) | 72 (Aug) | 61 (Dec) | 71 (Aug) |
| **Total** | | **664** | **669** | **672** | |
| | | | **2005** | | **652** |

*Note: HD = hot and dry; MD = moderate; WH = warm and humid; CD = Cold*

**Table 2 Study parameters and scales used**

| **Parameter** | **Scale** | | | | | | |
|---|---|---|---|---|---|---|---|
| *Thermal comfort field studies (TCS) 'Right Here, Right now'* | | | | | | | |
| Thermal sensation | Hot (+3) | +2 | +1 | Neutral (0) | -1 | -2 | Cold (-3) |
| Thermal acceptance | Unacceptable (1) | | | Acceptable (2) | | | |
| Thermal preference | To be warmer (1) | | | No change (2) | | | To be cooler (3) |
| Air movement satisfaction | Unsatisfactory (1) | 2 | 3 | 4 | 5 | 6 | Satisfactory (7) |
| Air movement preference | More air movement (1) | | | No change (2) | | | Less air movement (3) |
| Fan operation | OFF (0) | ON (1) | | Not available (N/A) | | | |
| Window operation | Shut (0) | Open (1) | | Partially open (2) | | Not available (N/A) | |
| *Building Use Studies (BUS) long term survey* | | | | | | | |
| Air stillness | Still (1) | 2 | 3 | 4 | 5 | 6 | Draughty (7) |
| Air quality | Unsatisfactory (1) | 2 | 3 | 4 | 5 | 6 | Satisfactory (7) |

Three responses related to thermal sensation, acceptance and preference, and two responses related to air movement satisfaction and preference from TCS were used for the analysis. From BUS, responses to the fields related to air stillness and satisfaction with the overall air quality were included. Status of fans and windows for each survey response was also recorded. The scales and values for each of these variables are given in Table 2.

**RESULTS**

**Indoor Climate**

Air velocity in naturally ventilated buildings is primarily a function of cross ventilation by opening of windows or the use of ceiling fans. In the NV dataset, the mean indoor air velocity observed was around 0.2 m/s (range = 0-1.96 m/s; SD = 0.4) across all seasons and climate zones. Figure 1 plots the mean, maximum and minimum air velocities for each climate zone-season aggregate for NV buildings. Of the four climate zones, the highest mean air velocity of 0.6 m/s was observed in warm and humid zone in monsoon and summer, and maximum air velocity of 1.96 m/s in monsoon, the highest of all other zones. This can be explained by greater use of ceiling fans or windows to reduce the discomfort resulting from high humidity and temperature. Hot and dry climate zone also presented trends of high values of mean and maximum air velocity. There was almost no variation in mean air velocity in cold climate zone. This is because ceiling fans were not available in any of the buildings surveyed and are not a common feature in buildings in cold climate. Across all climate zones, the highest mean air velocity occurred in summer (0.3 m/s) and the lowest in winter (0.1 m/s).

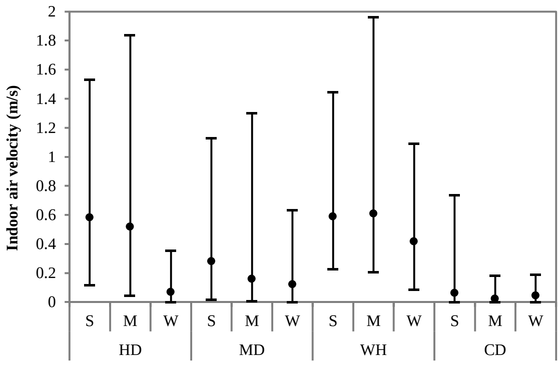


*Figure 1 Prevalent air velocities in NV buildings in different seasons and climate zones (S=Summer; M=Monsoon; W=Winter)*

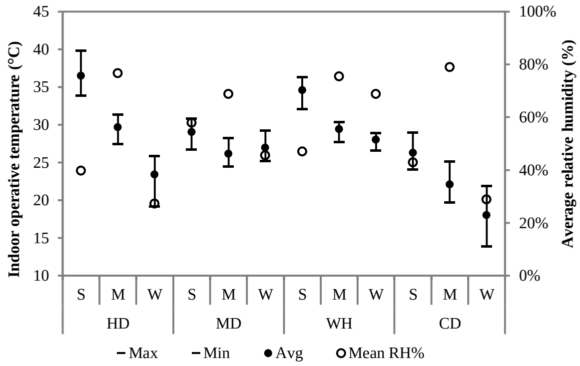


*Figure 2 Prevalent indoor operative temperatures and relative humidities in NV buildings in different seasons and climate zones (S=Summer; M=Monsoon; W=Winter)*

Comparing Figure 1 and Figure 2, it may be observed that the indoor operative temperature trends were followed closely by the mean air velocity trends – air velocities increased exponentially with increase in indoor operative temperature, till about 30 ˚C, beyond which there was no change. It was, however, difficult to relate mean air velocity with the variation in mean relative humidity. This may indicate that the increase in mean air velocity as an adaptive measure was, in most instances, related to adapting to high indoor temperature rather than high humidity levels.

Figure 3 plots the mean, maximum and minimum air velocities with respect to the mean indoor operative temperature. In the range of 21.5-29.5 ˚C, the relationship was best explained by expressing indoor air velocity as an exponential function of indoor operative temperature, explaining 80% of the variance in air velocity in NV buildings. Mean air velocities at indoor operative temperatures less than 21.5 ˚C were constant at 0.05 m/s and those at temperatures greater than 29.5 ˚C were constant at 0.6 m/s. This may be indicative of the limitations of changing the air velocity as an adaptive mechanism for very high or low indoor temperatures. Figure 4 examines the relationship between mean air velocity and outdoor 7-day weighted running mean air temperature. The exponential function explained 47% of the variance in air velocity with outdoor temperature. The relationship, however, was not as strong as in the case of indoor operative temperature in Figure 3.

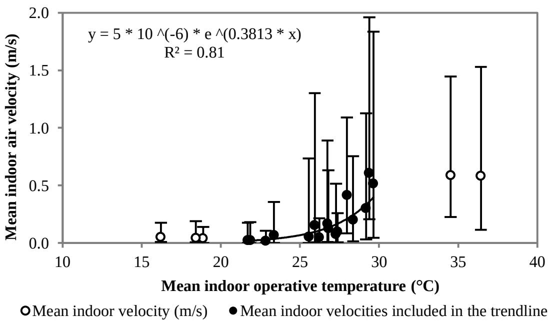


*Figure 3 Variation in air velocity with indoor operative temperature*

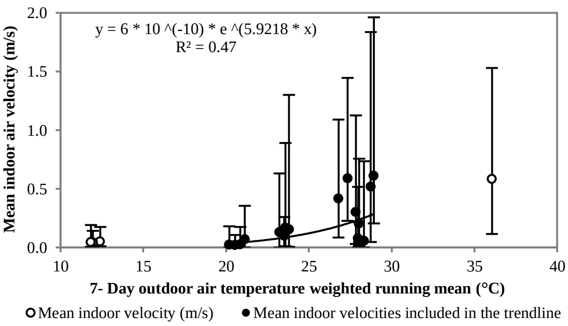


*Figure 4 Variation in air velocity with outdoor air temperature*

**Adaptive opportunities: status of fans and windows**

For almost all survey responses, fans were observed to be ON during all three seasons in the warm and humid climate (Figure 5). This may be to alleviate discomfort due to high temperatures in summer and high humidity levels in monsoon and winter. In hot and dry zone, almost all fans were reported to be ON in summer and monsoon and almost all were OFF in winter.

A more mixed use was observed in the moderate climate zone where fans were ON in 80% instances in summer and almost 25% in monsoon and winter. Cold climate zone did not have any fans available, except for a small fraction of 4-10% owing to isolated cases of table/wall mounted fans. Window use was highest in hot and dry and warm and humid climate zones in monsoon with 71-78% responses indicating open windows (Figure 7). 45-60% of the responses reported open windows in summer, across all climate zones. For monsoon and winter, however, the variation was greater.

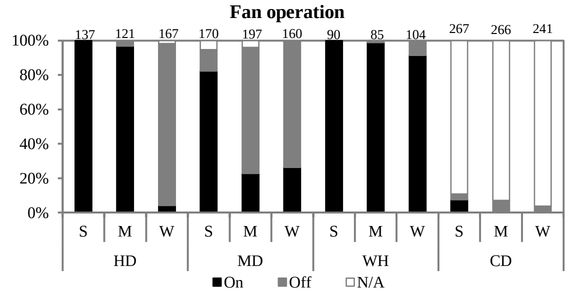


*Figure 5 Status of ceiling fan operation in NV buildings in different seasons and climate zones*

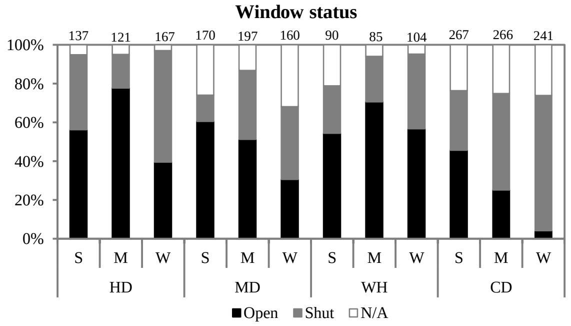


*Figure 7 Status of window operation in NV buildings in different seasons and climate zones*

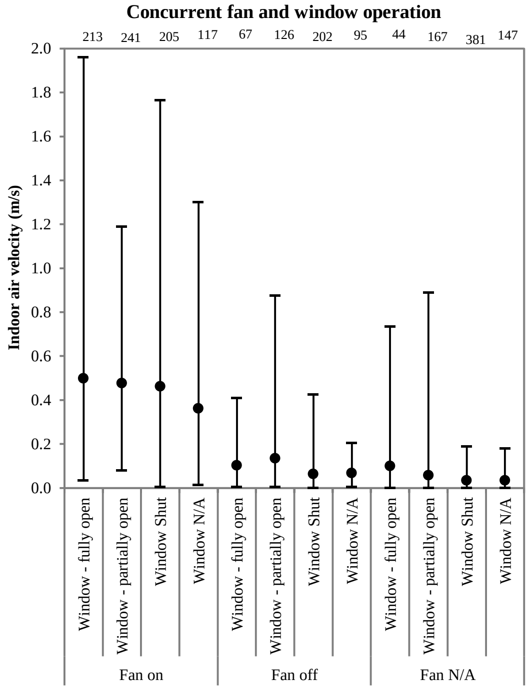


*Figure 6 Status of concurrent operation of ceiling fans and windows in NV buildings in different seasons and climate zones*

Figure 6 superimposes mean air velocity with fan and window operation. It clearly indicates that window use had little effect on mean indoor air velocity. When the fans were OFF or not available, opening or shutting the windows led to prevalent mean air velocities ranging from 0.06-0.13 m/s. On the other hand, when windows were shut or unavailable, operation of fans induced mean air velocities ranging from 0.36-0.46 m/s. In warm and humid zone, more than 90% fans were ON in all seasons. In hot and dry zone, almost 100% fans were ON in summer and monsoon.

In Figure 8, indoor operative temperatures were binned at 0.25 ˚C and percentage of fans and windows in operation was calculated for each temperature bin. A logit curve best explained fan operation with change in indoor operative temperature. It indicates that percentage of fans in ON mode increased exponentially with increase in indoor operative temperatures. When indoor operative temperatures were higher than 31 ˚C, all fans were ON and almost 90% of the fans were OFF below 25 ˚C. Figure 8 also shows window operation was used as an adaptive measure till the indoor operative temperatures reached 32 ˚C at which point all windows were open. Beyond 34 ˚C, occupants seemed to be shutting the windows, again as an adaptive measure to avoid excessive heat ingress from outdoors into their workspaces. A polynomial trend line ($R^2$=0.66) was used to capture occupant behavior more closely with actual operation. The polynomial curve, however, was still not able to explain the instances where all windows were open. A linear trend line ($R^2$=0.79) was then used which was able to explain window operation till 32 ˚C of indoor operative temperatures. Within this limit it indicated a significant relationship showing that with every 1 ˚C increase in indoor operative temperature, the proportion of open windows increased by 5%.

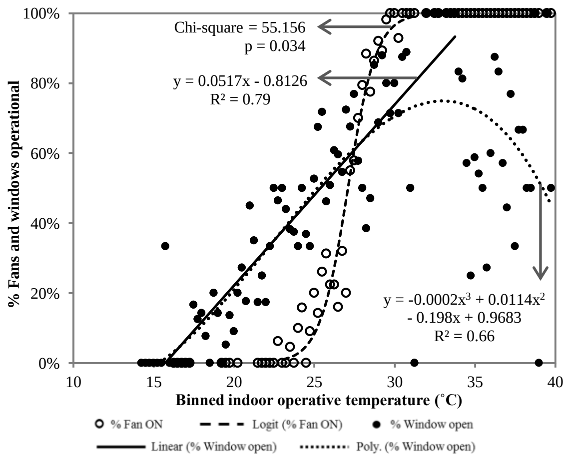


*Figure 8 Proportion on fans and windows in use in NV buildings expressed as a function of indoor operative temperature*

The figure establishes the use of fans and windows to alleviate discomfort owing to high indoor temperatures. It also indicates the level of indoor thermal conditions at which these adaptive measures were used. This provides a critical piece of information regarding occupant behavior that is important for building energy simulation but has not been available for workspaces in India.

**Impact of air movement on thermal comfort**

It is evident from Figure 9 that 65% of the people who voted neutral for thermal sensation also voted for no change in air movement. Almost 70% of people who voted 'hot' (+3) on the sensation scale preferred more air movement. Percentage of responses voting for no change in air movement decreased towards both ends of the sensation scale (hot and cold). The preference for more air movement, however, increased as the sensation votes moved towards +3. 57% of the people feeling 'slightly cool' preferred no change but a staggering 40% wanted more air movement. In Figure 10, almost 70% of the respondents voting for no change in the thermal environment did not want any change in the air movement. 65% of the people who wanted to be cooler also preferred to have more air movement. This agrees with the general idea that in an uncomfortably warm environment, people tend to want high air velocity as an adaptive measure. It is interesting to note, however, that more than 40% of people who were feeling cooler than normal (wanted warmer) also wanted more air movement even though more air movement would make them cooler than they felt. Almost 60% of the people who found their thermal environment unacceptable voted for more air movement (Figure 11). About the same ratio wanted no change in air movement among those who voted the thermal conditions as acceptable. Almost 43% of the respondents in NV buildings wanted more air movement and 3% wanted less air movement.

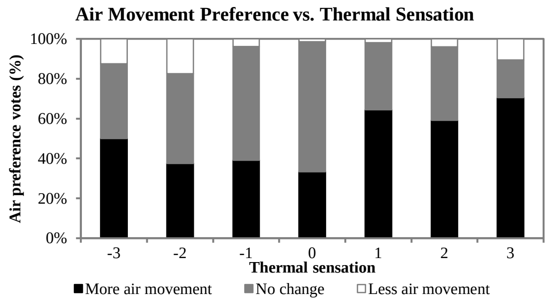


*Figure 9 Distribution of air movement preference votes on the thermal sensation scale*

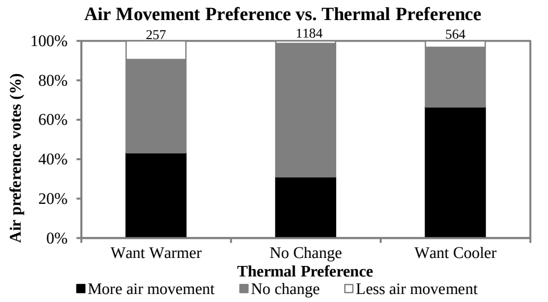


*Figure 10 Distribution of air movement preference votes across thermal preference response categories*

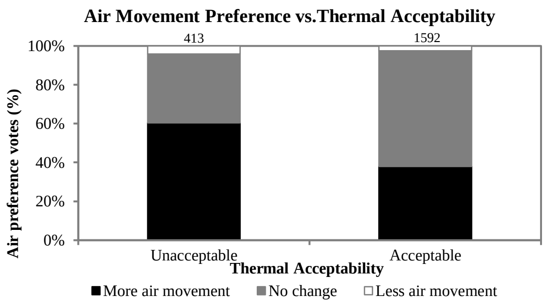


*Figure 11 Distribution of air movement preference votes across thermal acceptability response categories*

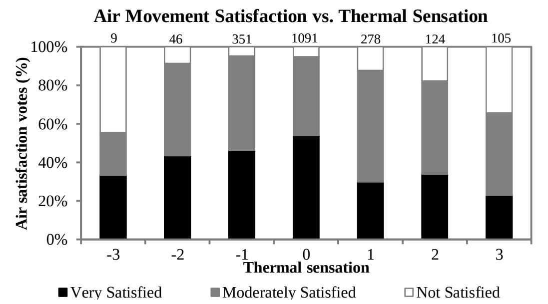


*Figure 12 Distribution of air movement satisfaction votes on the thermal sensation scale*

In order to assess air movement satisfaction, the 7-point scale from Table 2 was converted into a three-point scale by merging the responses in the first two categories into one 'not satisfied' category and merging the last two into 'very satisfied'. The central three categories formed 'moderately satisfied'. The number of votes (%) was then plotted against thermal sensation (Figure 12). Among the subjects who voted for neutral thermal sensation, 54% were very satisfied, 41% were moderately satisfied and 5% were dissatisfied with air movement. The percentage of dissatisfied respondents increases as the sensation moves towards ±3 vote. Almost 35% of the respondents voting 'hot' are dissatisfied with the air movement. Interestingly, this percentage increases to 45% for those voting 'cold'. 60% subjects who did not want to change their thermal environment were moderately satisfied with the air movement.

Almost 85% of the people who were very satisfied with the air movement did not want any change but 15% wanted more air movement (Figure 13). This suggests a discrepancy between air movement satisfaction and preference. Of those who were moderately satisfied with the air movement, 60% wanted more air movement. It is important to note, however, that 95% of the subjects not satisfied with air movement wanted more air movement in the work space.

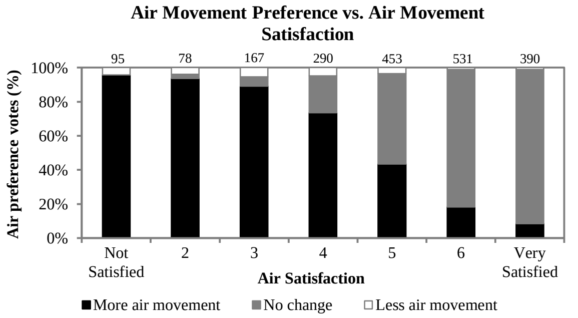


*Figure 13 Distribution of air movement preference votes on the air movement satisfaction scale*

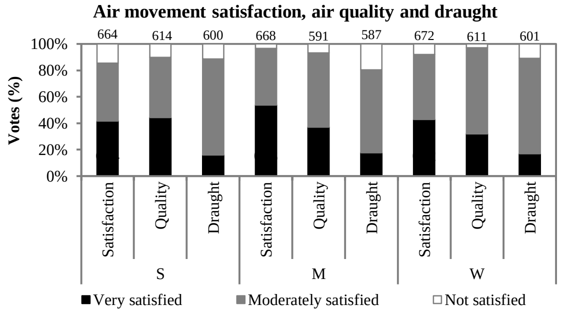


*Figure 14 Comparison of air satisfaction votes from TCS with the air quality satisfaction and air draught votes from BUS*

Reponses related to overall air quality and draught from the BUS questionnaire were compared with air movement satisfaction (Figure 14). It is important to note here that the BUS survey was administered in the seven NV buildings in the monsoon season. So, the responses to air quality and draught for summer and winter seasons were based on respondents' memory of their experiences related to these aspects of the work space. Draught does not seem to be a problem in the NV buildings, with only 10-20% of the subjects interviewed reporting draught across three seasons. Almost 60-70% responses indicated that the workspaces were moderately draughty. Reponses to the question of air quality satisfaction indicate 30-45% subjects being very satisfied and 45-65% being moderately satisfied. Maximum dissatisfaction responses of 10% occur in summer season.

## CONCLUSION

The results from the study revealed the range of air velocities prevalent in NV office buildings in India, reaching as high as 2.0m/s. Indoor air was nearly still (average air velocity < 0.1 m/s) in cold climate zones across all seasons. Mean air velocities in all seasons in warm and humid zone were highest (0.4-0.6 m/s) as compared to other climate zones. They were closely related to the indoor operative temperatures and increased exponentially from 22-30 ˚C. Below 22 ˚C, mean air velocities were less than 0.1m/s and above 30 ˚C indoor operative temperatures, they were constant at 0.6 m/s. This indicated that high air velocity was used as an adaptive measure to address discomfort due to indoor warmth rather than humidity. There was a strong relationship between mean indoor air velocities and indoor operative temperatures. The dependence of mean air velocities on outdoor warmth, however, was not very robust.

Fans and windows are very important adaptive measures for subjects working in naturally ventilated spaces. That said, higher air speeds were primarily a contribution of fans (0.3-0.4m/s) and windows had a limited role (<0.06 m/s) to play. One may suggest that more than the need for higher air movement, windows were opened for other reasons such as cooling the indoors (when outdoor is pleasant), fresh air, daylight and view.

Window use also showed a very robust correlation with indoor operative temperature explained by a linear trend till 32˚C indoor operative temperature. Occupants started operating windows when the indoor operative temperatures reached 15 ˚C. All windows were open between 32-34 ˚C and closed again when temperatures approached 34 ˚C. The logit regression predicted that ceilings fans started operating at 23 ˚C and 100% of the fans were in use at 31˚C and higher indoor operative temperatures.

The study also shows that the office workers in India tend to prefer more air movement, or higher air velocities. Even when they found the thermal environment acceptable, almost 40% wanted more air movement. Respondents' dissatisfaction with air movement was primarily due to the lack of it. Air movement preference and satisfaction were closely related to thermal sensation. Subjects preferred more air movement as the sensation moved towards the either end (+3 and -3) of the 7-point sensation scale. At +3, 70% respondents wanted more air movement and at -3 the percentage of respondents wanting more air movement was 45%. Even when subjects were cooler than they would like, they wanted higher air movement.

Most importantly, the study provided valuable insights into occupant behavior in office buildings. Some of the results from this study could be used to better inform the simulation models that are usually very different from the real buildings. The results give very clear indications of how fans and windows are operated in naturally ventilated office buildings and could help build operation schedules for building energy simulation.

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## NOMENCLATURE

TCS = Thermal Comfort instantaneous survey
BUS = Building Use Survey
HD = hot and dry climate zone
MD = moderate climate zone
WH = warm and humid climate zone
CD = cold climate zone
S = summer
M = monsoon
W = winter
NV = fully naturally ventilated buildings

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