Comfort and adaptation in mixed-mode buildings in a hot-dry climate

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Abstract

Mixed mode (MM) buildings open up a new arena for energy efficient design. Zoned MM buildings are the most common, particularly in the developing world where only some areas in a building are air-conditioned (AC) based on programmatic requirements while the rest of it is naturally ventilated (NV). Occupants in the NV zone frequently visit the AC zone and are well aware of the conditions there. The unanswered question in such a MM building is whether occupants in the NV zone have similar adaptive behaviour and thermal comfort opinions as those in purely NV buildings or are they possibly influenced by higher expectations created from the AC zone visits.

A transverse (cross-sectional) study was conducted between April 2011 to July 2013 in the hot and dry climate of Jaipur, India, including 2869 total survey responses, out of which 604 were from zoned type MM buildings. Mixed mode observations were available only during summer (April-August 2011). Occupants were asked about their 'right-now' opinion of indoor environmental quality variables such as thermal and humidity sensation, air movement and comfort. Simultaneous physical measurements of air and radiant temperature, relative humidity and air speeds were also recorded. We analyse the results examining the physical conditions and thermal comfort responses in both the zones, and adaptive actions exercised in the NV zone. We compare the observations from the NV zone to three adaptive comfort charts to evaluate whether comfort in the NV zone in a MM building can be modelled as a purely NV building.

Keywords: Mixed mode, zoned type, adaptive action, thermal comfort

1. Introduction

Since the development of the adaptive comfort theory, researchers have conducted many field studies in naturally ventilated (NV) and air-conditioned (AC) buildings to evaluate comfort and adaptive actions. NV buildings consume significantly lower energy as compared to AC and also maintain similar or improved comfort levels (Loftness et al., 2007). However, it is commonly found that a building is not always fully naturally ventilated or fully air-conditioned but sometimes combines both conditioning strategies; these are referred to as 'mixed mode' (MM) buildings. The temporal and spatial method of cooling the space further classifies the mixed mode building as changeover, zoned and concurrent type (Center for the Built Environment-mixed mode website).The MM buildings discussed in this paper are all zoned type; part of the floor area is conditioned and the rest naturally ventilated. From now on they will be referred as 'AC zone' and 'NV zone' respectively.

MM buildings have a great potential for energy efficient design when the major responsibility of maintaining appropriate space temperature is borne by passive design elements, and air-conditioners are used only to meet programmatic requirements such as computer lab/conference room, or weather conditions with overly warm

temperatures. MM buildings also perform well as compared to purely NV and purely AC buildings in thermal comfort and air quality (Brager and Baker, 2009).

Although MM buildings are becoming common, there are not many studies that have evaluated comfort and adaptation in these buildings. Studies that have led to the adaptive comfort standards show clear evidence that occupants in NV buildings are comfortable over a broader temperature range than in AC (ASHRAE Standard 55, 2004, Brager and de Dear, 1998, Nicol and Humphreys, 2002); the unresolved question is whether the adaptive theory can be extended to MM buildings. In a zoned MM building, occupants in the NV zone frequently shuttle to the AC zone during the day and are aware of the environmental conditions in the AC zone. As a result, they might have higher comfort expectations. Contrary to this point, access to adaptive opportunities like operable windows and fans might outplay the expectancy factor. In a zoned type MM building studied in Sydney Australia, occupants in the NV zone adapted using passive means and accepted a wider indoor temperature compared to AC zone (Rowe, 2004). Testing the hypothesis of expectation in a switchover type MM building, Deuble and de Dear found that status of the air-conditioner influenced occupant's thermal response. When the physical conditions were associated with a PMV value of +1, the actual occupant votes revealed a warmer thermal response in AC mode as compared to NV mode (Deuble and de Dear, 2012).

Understanding thermal expectation, comfort response and physical environmental conditions in a MM building is crucial for a developing country like India where it is estimated that two-thirds of the commercial area needed by 2030 is yet to be built (Singh et al., 2013). Room air-conditioner sales are fast growing and have doubled from 400,000 units in 2006 to 800,000 units in 2011, accounting for highest energy consumption in the energy sector. The estimated installed inventory of AC's by 2016 is 10.2 million which, needless to say, would mount unrealistic pressure on power plants (Phadke et al., Natural resources defense council (NRDC), 2013, World Bank report, 2008).

Designers have a choice for these buildings that are yet to be built; seal them completely and install air-conditioners or adopt a more sustainable approach of selectively air-conditioning spaces only when and where needed, and design the rest of it to be naturally ventilated by deploying rigorous passive design strategies. To be able to opt for the later, the environmental conditions and the corresponding influence of expectancy on the occupants in the NV zones of a zoned type MM building needs to be characterized.

Specifically, the objectives of this analysis of the field study data are:

1. Evaluate the temperature, humidity, air speed and CO_2 concentration in the AC and NV zones.
2. Evaluate the adaptive control actions of window, fan, blind/curtain and balcony door operation in the NV zones.
3. Evaluate thermal comfort responses (thermal sensation/comfort) in the AC and NV zones.
4. Evaluate whether the NV zone of MM buildings can be modelled as a purely NV building, using the existing adaptive comfort model.

2. Methodologies

A transverse field study was conducted in the hot and dry climate of Jaipur, India, including 2869 total survey responses (1418 responses were from 17 purely naturally ventilated buildings, 642 from 6 purely AC, and 809 from 13 mixed mode buildings, out of which 560 were from 11 zoned type buildings.). Amongst the 560 responses, 274 responses were from NV and 286 were from AC zone; both having desk based work. Mixed mode observations were recorded only during summer (April- August).

The survey asked occupants about their clothing and activity patterns; thermal sensation, comfort, humidity and air movement sensation; temperature and air movement preference; and a few personal history questions, such as the use of air- conditioners at home and in cars. Using the class-II protocol of field measurement (de Dear, 1998), the study recorded parameters such as indoor temperature, relative humidity, mean radiant temperature and air velocity. Data about adaptive actions such as operating fans, windows, doors and blinds/curtains was also collected.

A weather station installed on a university campus (within 5 km radius of the surveyed buildings) recorded outdoor air temperature, humidity, rainfall, wind speed and direction.

3. Descriptive statistics

3.1. Climate analysis

Jaipur is a hot and dry climate. Summers are from the month of April to October with hot afternoons (mean = 30.97˚C, SD = 4.5˚C, maximum = 43 ˚C) (Figure 1). Mean value of relative humidity during summer is 53%. Winters are cold and occur during the months of November – February (mean = 19.8˚C, SD = 4.7˚C, lowest = 7.2˚C) and mean relative humidity during winter is 41%.

Warm wind is prevalent during summer (Figure 2); outdoor wind speed in summer (mean = 4.73 m/s, SD = 2.26 m/s) is higher than winter (mean = 2.94 m/s, SD = 1.7 m/s).

The weather is mainly cooling-dominated and thus presents a challenge for designing an energy efficient building that minimizes air-conditioning use, while also providing comfort.
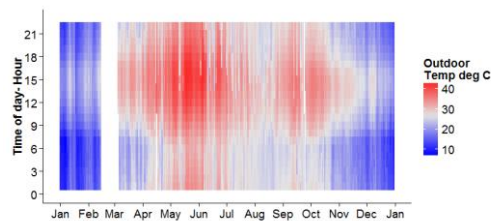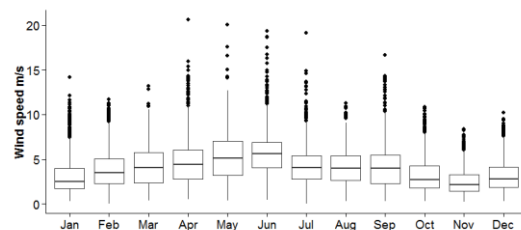

Figure 1 Heatmap of Jaipur weather

Figure 2 Outdoor wind speed

3.2. Age/gender distribution

India is witnessing an increase in the working age ratio which bestows upon it a 'demographic dividend' for economic growth (Aiyar and Mody, 2011). This finding has subtle implications on thermal comfort evaluation and design of future low energy

buildings. The young working age population (below 35 years of age) represents the future demands for comfort and understanding their current thermal opinion can help map out the pattern of comfort expectation. In our dataset the percentage of occupants below the age of 35 is 63% in the 'NV zone' and 57% in 'AC zone' (Figure 3).
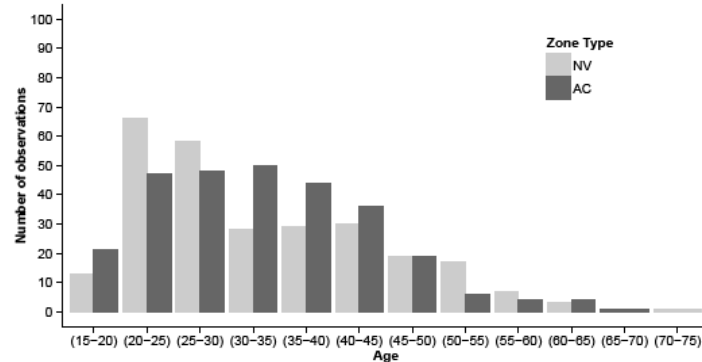

Figure 3 Age distribution in NV/AC zone

4. Physical measurements

4.1. Temperature/humidity distribution

Indoor operative temperature in the AC zone floated between 23 – 29˚C while the NV zone indoor temperature was warmer, and ranged between 29 – 36˚C (considering only those bins with more than 20 observation). Humidity level was also affected by the presence of AC, as would be expected. Humidity was maintained below 50% in 91% of the 'AC zone' observations, while the humidity shot above 50% in 50% of the NV zone observations (Figure 5). This significant difference in temperature and humidity between the AC and NV zone is particularly important because these two variables are of great concern while designing MM buildings in tropical climate. Other studies conducted in tropical climate have found that occupants are acceptable of higher indoor temperature and humidity in NV buildings (Nicol, 2004, Busch, 1992, Indraganti, 2010, Mallick, 1996). We test this hypothesis in this paper for the unique situation in a MM building where the occupants in the NV zone are well aware of the lower temperature and humidity in the AC zone.

Figure 6 shows the indoor – outdoor temperature occurrences in both the zones. The dotted line is where the indoor temperature equals outdoor. Interestingly, indoor stayed cooler than outdoors for 80% of the observations in the NV zone. This was mainly because the NV zones were shielded from direct solar radiation (by balconies and corridors) in most of the buildings and the construction material had high thermal mass. These buildings were constructed with conventional building practices such as double height ceiling, low window to wall ratio (20 – 30%), thick stone walls with plaster on both sides (330 mm) and also brick construction (double brick type - 229 mm) with plaster.

Overlaying the observations on the psychrometric chart (Figure 7) shows that 58% of the observations from the AC zone were inside the comfort zone defined by ASHRAE Standard 55. When the physical observations were inside the comfort zone, in 99% of these occurrences the occupants voted that they were comfortable. However, even when

the physical observations were outside the comfort zone, there was still a high number - 93% who were comfortable. The NV observations were clearly outside the comfort zone. In these NV zone observations, occupants voted to be comfortable 80% of the time when indoor temperature was less than 33 ˚C.
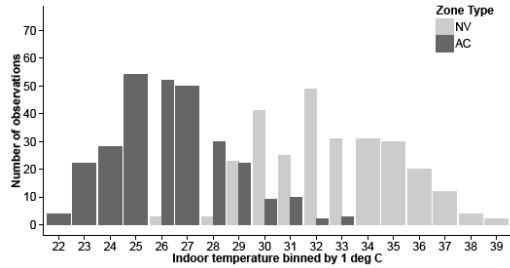

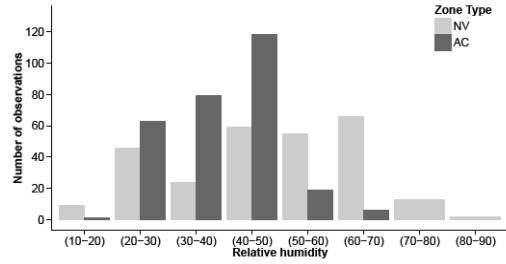Figure 4 Indoor temperature distribution in NV/AC zone
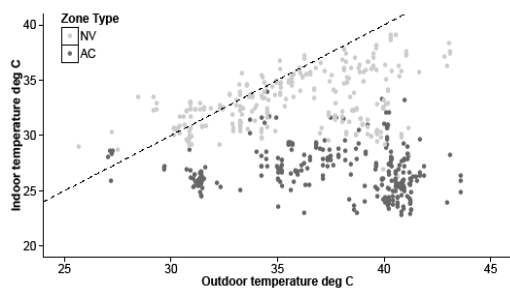

Figure 5 Humidity distribution in AC/NV zone

Figure 6 Indoor/outdoor temperature distribution in NV/AC zone
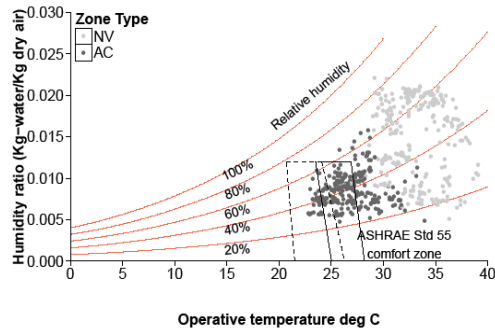

Figure 7 Observations overlaid on the psychrometric chart

4.2. Humidity sensation and air movement in NV zone

Although, Jaipur has a dry climate, 50% of the observations in the NV zone were found to have relative humidity above 50%. Figure 8 shows the humidity sensation of occupants in the NV zone for different relative humidity bins. Although humidity sensation is above neutral for relative humidity above 50%, the median lies at "Slightly humid" and there were negligible votes at "Very humid". The forgiving humidity sensation could be because of air movement, which is shown in Figure 8 for different temperature bins, for both the NV and AC zones. Air movement is seen to be significantly higher (p<0.05) in the NV zone compared to the AC zone in two of the four temperature bins with overlapping observations (represented by a solid dot just above the x axis). The horizontal dotted line shows the ASHRAE recommended limit for draft 1.2 m/s (ASHRAE Standard 55 2010b). Based on these physical measurements, 24% of the observations in the 'NV zone' were found to have air speed more than 1.2 m/s while it was only 3% in the 'AC zone'. In the NV zone, mean air speed for indoor temperatures above 25˚C was 0.9 m/s, which is higher than the mean air speed found for Pakistani subjects (0.45 m/s) in NV buildings in the same indoor temperature range (Nicol et al., 1999).

Investigating the indoor air speed at high humidity, Figure 9 shows the range of air speed for different relative humidity bins. We do the analysis just for the NV zones since humidity above 50% was rarely observed in the AC zones (Figure 5). Air speed at humidity above 50% in the NV zone is quite high around 1 m/s (Figure 9). The high

air velocity in the NV zone hints at occupant's tendency to use windows and fans to keep themselves comfortable at higher temperature and humidity, as observed in other field studies carried out in NV buildings in tropical (Cândido et al, 2011; de Dear et al, 1991; de Dear and Fountain, 1994; Mallick, 1996; Nicol, 2004; Sharma and Ali, 1986)

The mixed mode configuration brings forth another perspective to the findings; can comfort be provided in the NV zone by ensuring adequate opportunities to adjust air movement in the space, even when occupants are intermittently exposed to conditions of the AC zone where comfort is achieved predominantly be temperature control?
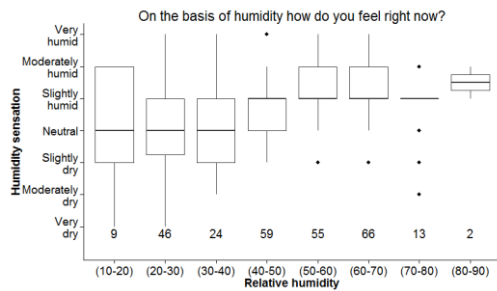

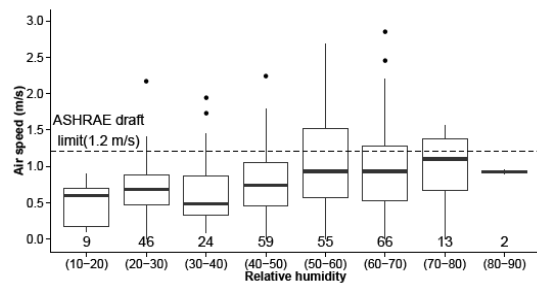Figure 8 Humidity sensation binned by relative humidity in NV zone

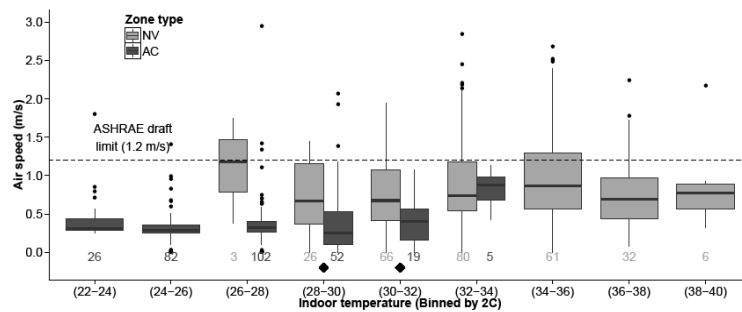Figure 9 Air velocity binned by relative humidity in NV zone

Figure 10 Air speeds in NV/AC zone binned by indoor temperature

4.3. CO$_2$ concentration

Significant relationship between sick building syndrome and CO$_2$ concentration has been observed at a threshold of 800 ppm (Apte et al., 2000). Results from CO$_2$ monitoring show that concentrations in the NV zone are much better than in the AC zone. 88% of the observations in the NV zone have a CO$_2$ concentration less than 800 ppm as compared to only 51% in the AC zone (Figure 11). Surprisingly, 50% of the observations in the AC zone recorded CO$_2$ concentration of above 2400 ppm. This could be because windows were never opened in the AC zones and they did not have any provision for mixing fresh air especially in offices with high occupancy. For comparison, the average office floor area per occupant in government offices the US is 20 m^2, while it is only 5-10 m^2 in Indian offices (Singh et al., 2013). Although a short-term exposure to CO$_2$ concentration above 2400 ppm is not harmful to health, it can prove to be a concern if the conditions prevail for a long time. The high CO$_2$ concentrations can also cause discomfort due to bio effluents (Persily, 1997, ASHRAE Standard 62.1 2010a).
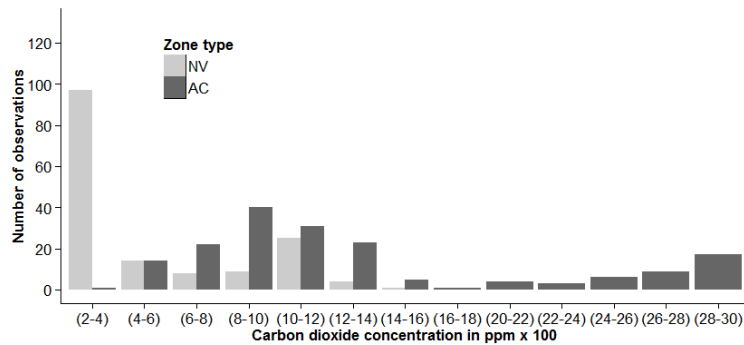
Figure 11 CO_2 concentration in NV/AC zone of MM building

5. Use of adaptive control in NV zone

Thermal comfort is directly influenced by behavioural adaptation in addition to psychological and physiological adaptation (Brager and de Dear, 1998). By extending the opportunities for behavioural adaptation in mixed mode buildings compared to conventional sealed buildings, the question becomes whether occupants in the NV zone use these adaptive actions to the same degree as in purely NV buildings. European and Pakistani mixed mode buildings have been found to follow similar control patterns of window opening and fan operation as in purely NV buildings (Rijal et al., 2008). In this paper, we do a descriptive analysis of window, fan, blind and balcony door use in the NV zone per degree indoor temperature to evaluate the proportion of usage in each bin. We chose indoor over outdoor temperature as the metric for binning because it captures the information at the individual building level which might vary from building to building for the same outdoor temperature, as noted by Robinson (Robinson, 2006).

5.1. Windows
Windows in the AC zone were closed in all the observations while those in the NV zone were sparingly opened; only 38% open overall (Figure 12). The bar graph does not show any clear trend and it seems like fewer windows are opened at indoor temperatures above 37˚C. This might be because outdoor temperature is warmer than indoors in 80% of the observations (

Figure 6).The benefit of purging the warm indoor air and the disadvantage of bringing in even warmer outdoor air seem to be acting against each other.

5.2. Fans
Fans were found to be on in 98 % of the observations in the NV zone. This result is contrary to other studies that found windows to be the most widely used control option (Haldi and Robinson, 2008, Liu et al., 2012). However, the high percentage of fan use reveals that occupants like to have air movement. It also partially explains the window opening behaviour; when the outdoor temperatures are higher than indoors, occupants prefer to keep their window closed and turn on the fans to provide air movement, which is an appropriate strategy.

5.3. Blinds/curtains
Adjusting blinds is an important adaptation strategy in tropical climates since direct sunlight or glare is thermally and visually unpleasant at high indoor temperatures. Overall, 68% of the blinds were found to be open in the NV zone (Figure 14). Fewer

blinds were found open as the indoor temperature increased above 33°C, possibly to avoid heat gain and glare.

5.4. Balcony doors

Overall, 72% balcony doors were open. Balconies are an integral part of climate responsive building design in tropical climates as they act as thermal buffer zones, reducing the direct solar exposure to the interiors while providing air movement. In most of our buildings, balconies were located on the side of the façade that received direct sunlight; towards South and South-west.
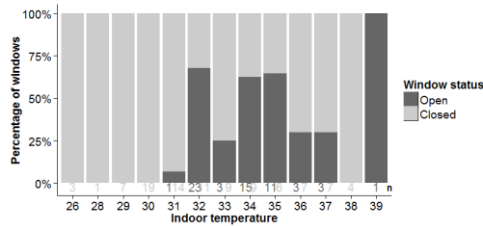

Figure 12 Percentage of windows open/closed in the NV zone of MM
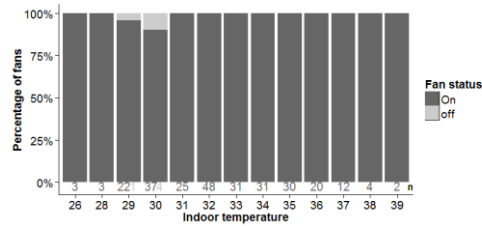

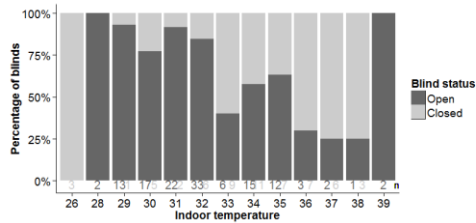Figure 13 Percentage of fans on/off in the NV zone of MM

Figure 14 Percentage of blinds open/closed in the NV zone of MM
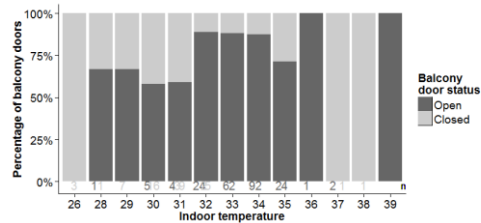

Figure 15 Percentage of balcony doors open/closed in the NV zone of MM

5.5. Comparison with purely NV buildings

In the 17 purely naturally ventilated buildings surveyed and monitored in this study, similar degree of adaptive control usage was observed for windows and fans. Overall, windows were open in 33% and fans were turned on in 81% of the observations. Interestingly, all of the 42 observations at indoor temperature above 36 °C had windows open. Blinds were open in 58% while balcony doors were open in 83% of the observations.

6. Thermal comfort

6.1. Thermal sensation in AC and NV zone

Overall, occupants in 70% and 87% of the observations in NV and AC zones, respectively, voted within the thermal sensation limit of ±1 (slightly cool – slightly warm). Figure 16 shows the box plot of thermal sensation votes in both the zones for bins of indoor temperature. When the indoor temperatures were between 30°C – 38°C in the NV zone, the median value of thermal sensation was "slightly warm". This indicates that occupants in the NV zone do not feel overly warm at higher indoor temperatures and adapt themselves to the indoor conditions using controls such as operable windows, fans, blinds and balcony door. This is particularly interesting because of the expectancy factor discussed earlier, where there was concern that NV occupants' visits to the AC zones would lead to their desire for cooler temperatures.

Our results show that adaptation to the warmer temperatures in the NV zone overrides expectation that may have been influenced by the AC zone.
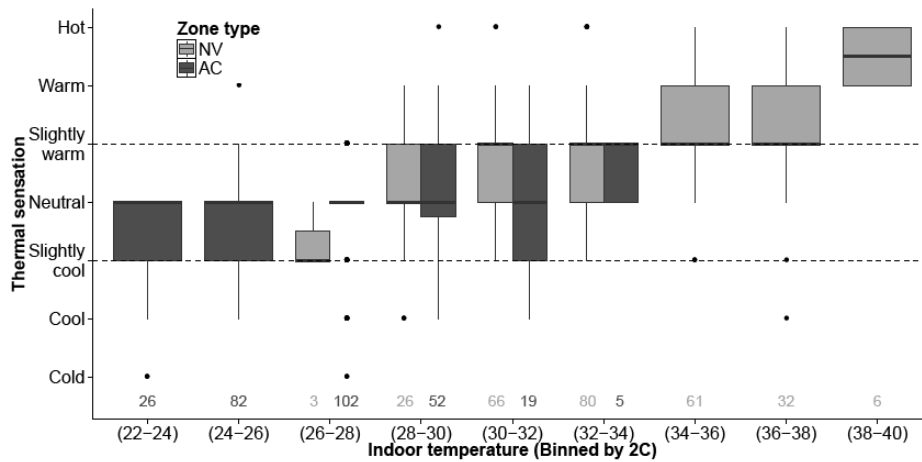

Figure 16 Thermal sensation Indoor temperature range

6.2. Relation between thermal sensation and comfort

The most appropriate metric for thermal comfort has often been debated because of its inherent subjective definition. The ASHRAE Standard 55 adaptive model uses thermal sensation as the metric to calculate the percentage of people satisfied. However, thermal sensation doesn't necessarily reflect an occupant's comfort opinion. An occupant might vote that to feel warm, but may still be comfortable. This might be due to the three adaptations pointed out in the adaptive comfort theory- behavioural, physiological and psychological, or because of the pleasant experience in transient temperature conditions (Brager and de Dear, 1998, Kuno, 1995).

In our survey, occupants recorded their comfort opinion on a scale of 5 (Very uncomfortable- Very comfortable). Figure 17(NV) and Figure 18(AC) shows percentage of occupants comfortable (colour), binned per degree indoor temperature and thermal sensation. Only those bins with five or more observations are shown. Interestingly, the range of thermal sensation is much broader in the NV zone on the warmer side while it is broader on the cooler side in the AC zone. In the NV zone, when the indoor temperature was between 30-35°C, occupants voted to be "neutral" or "slightly warm" in 73% of the observations (123 out of 169). Out of these 123 observations, 84% were comfortable (Figure 17). Occupants in the AC zone voted to be comfortable in 96% of the observations (Figure 18). However, there are some slightly cool and cool votes that occur at indoor temperature of 24 -27°C which shows that these AC zones run a potential risk of overcooling the building. The comparison of thermal sensation and comfort between NV and AC zone illustrates that in a hot-dry climate, air-conditioners do a good job in providing comfort, but it is also possible to keep occupants comfortable without having to use an air-conditioner.
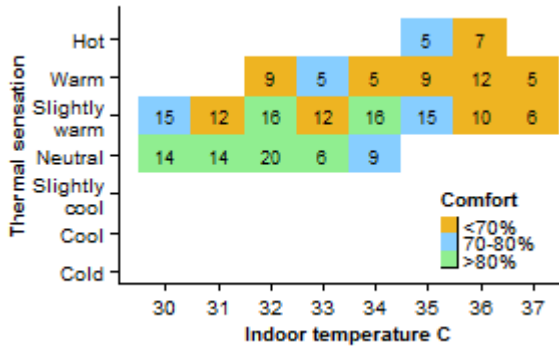
Figure 17 Percentage comfortable per degree indoor temperature and thermal sensation in NV zones
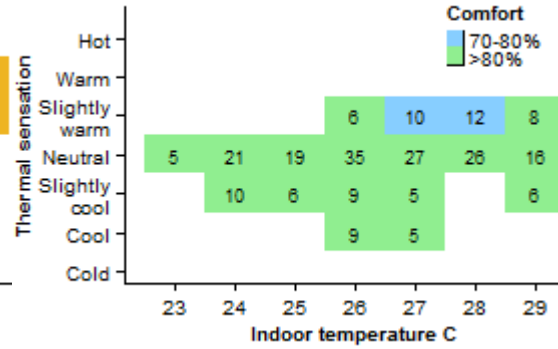

Figure 18 Percentage comfortable per degree indoor temperature and thermal sensation in AC zones

6.3. Comfort temperature range in NV and AC zone

In the NV zone more than 70% occupants voted to be comfortable per degree indoor temperature ranging from 29˚C – 34˚C, while in the AC zone the range was 23˚C – 29˚C (considering only those bins with more than 20 votes). The higher comfort temperature range in the NV zone clearly supports the adaptive theory which posits the acceptance of a wider range of comfort temperature. The upper limit of the observed comfort range in the AC zone is also higher than the one defined in ASHRAE Standard (Figure 7), which basically means occupants in the AC zone also adapt to warmer than neutral indoor temperatures.

When viewed from the perspective of a mixed mode building, the comfort range presents an interesting scenario. Two groups of people in the same building are exposed to a relatively low and high temperature range (AC and NV zone). The ones in the lower temperature range are comfortable; but the majority of those in the higher temperature range, barring a few observations when the indoor temperature is greater than 35 ˚C, are also comfortable. This is a promising result for new constructions in tropical climates which can rely more on passive design to provide comfort cost efficiently.
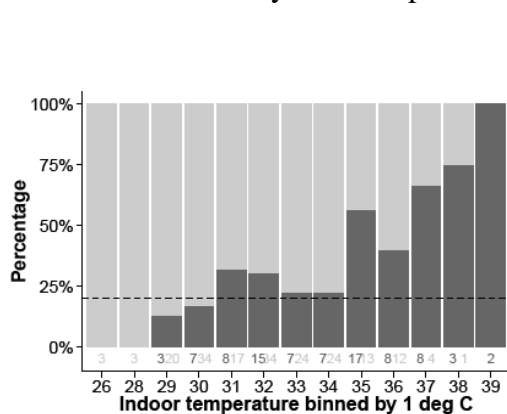

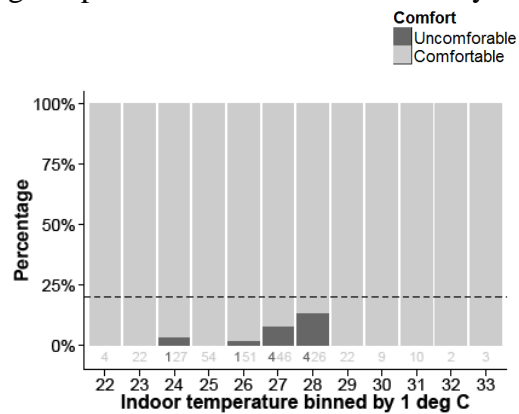Figure 19 Percentage people dissatisfied in NV zone binned by indoor temperature

Figure 20Percentage people dissatisfied in AC zone binned by indoor temperature

6.4. Comparison of NV zone temperature with ASHRAE Standard 55, EN 15251 and an adaptive chart developed for hot-humid Indian climate

ASHRAE adaptive standard 55 gives a relation between running mean temperature and comfort temperature in an unconditioned building, but does not provide any guidelines for modelling comfort in a mixed mode building. However, it allows the comfort model to be applied in spaces that do not have a mechanical cooling system installed (ASHRAE Standard 55, 2004). EN 15251, on the other hand, gives similar relationship between comfort and running mean temperature while extending the applicability of the standard to spaces that have mechanical conditioning installed but not in operation (Nicol and Humphreys, 2002).Technically, both the adaptive models can be applied to the NV zone of a mixed mode building.

To verify this hypothesis of applicability of the adaptive models in the NV zone, we compare the percentage of people comfortable in our study with the ASHRAE Standard 55, EN 15251 and an adaptive model developed for hot-humid climate of South India (Indraganti et al., 2014) (Figures 20-22).

Only 53% (145 out of 274) of the observations in the NV zone were in the temperature range where ASHRAE adaptive chart is applicable (i.e., running mean outdoor temperature less than 33˚C) (Figure 21). Of the 274 total NV zone observations, only 20 were inside the 80% satisfaction zone (outermost lines) defined by the adaptive chart (Figure 21), and 85% of these 20 occupants voted that they were be comfortable. But there was still a very high level of comfort above the adaptive comfort zone limits. In the area above the 80% satisfied limit, but below the running mean 33˚C limit of applicability (shown in a dotted blue line), 75% occupants were comfortable. When running mean was greater than 33 ˚C, occupants voted comfortable in 60% of the 129 observations.

Comparing with EN 15251 standard (Figure 22), only 57 of the 274 observations fell in the temperature zone where the adaptive chart is valid (running mean temperature less than 30 ˚C). This is probably because EN 15251 was developed from field study data from European countries, which did not have hot summers like Jaipur (Nicol and Humphreys, 2002). We do not evaluate further with respect to EN15251 due to the limited number of valid votes.

For the adaptive chart developed from a field study in hot-humid climate of South India (Indraganti et al., 2014), 53% observations from the NV zone were within the temperature range where the chart was valid (running mean temperature less than 33 ºC) (Figure 23). Considering ± 4K deviation from neutral temperature as the comfort threshold, 81% occupants voted to be comfortable inside the comfort zone. Out of the 56 observations that were outside the comfort range, 70% were comfortable.

These results indicate two things:
- The NV zone of mixed mode can be modelled as a purely naturally ventilated building, while noting that in this particular study we found high degrees of comfort at temperatures even high than the recommended upper limits
- Amongst the three adaptive charts compared above, ASHRAE Standard 55 and the adaptive model developed by Madhavi et.al. best represent comfort from this tropical climate better than EN15251.
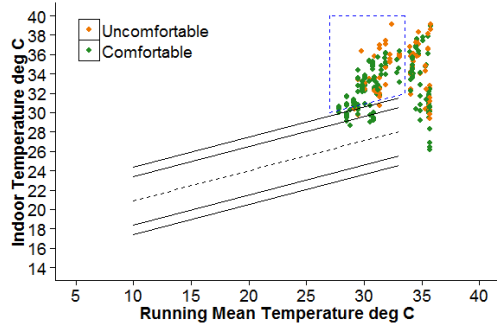
Figure 21 Comfort votes from NV zone overlaid on the ASHRAE Standard 55 adaptive chart
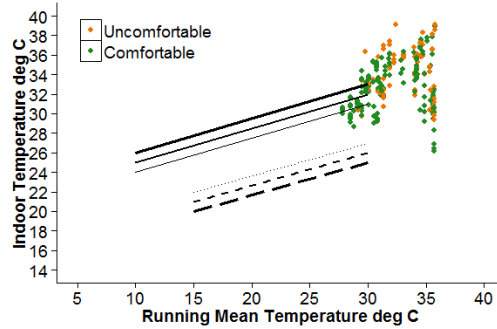

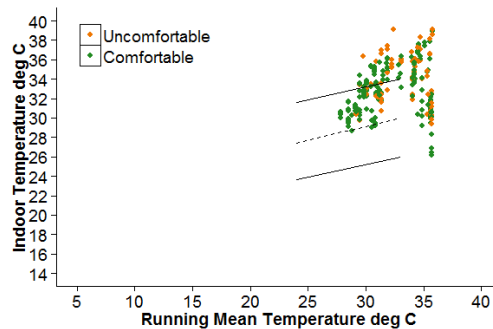Figure 22 Comfort votes from NV zone overlaid on EN 15251 adaptive chart

Figure 23 Comfort votes from NV zone overlaid on adaptive chart developed by Madhavi et.al. for South Indian climate

7. Discussion

Physical measurements and thermal comfort survey responses from this study shows that a zoned-type mixed mode building has the potential to save energy and also provide comfort.

Indoor temperatures in the NV zones were found to be on an average 2 - 5 ˚C lower than outdoor temperature even when the outdoor temperature was above 35˚C Figure 6). In addition to revealing that the building envelope is performing well in a hot-dry climate, this result when viewed in the light of thermal comfort raises an interesting question- Is the comfort opinion of a space driven by the difference in indoor and outdoor temperature, as opposed to the absolute value of either one of them? In other words, if it is very hot outside a temperature drop of few degrees indoors could be sufficient to keep occupants comfortable.

High air speeds at higher relative humidity and temperature, apparently due in part to the frequent turning on of fans in the NV zone, shows that occupants prefer to have air movement. In addition to this, 70 - 80% comfort at a high indoor temperature range of 29 – 34 ˚C is an evidence of thermal adaptation where occupants are comfortable beyond the neutrality defined by the uniform conditioning-based PMV method. Occupants' ability to adapt to the high humidity and temperature in the NV zone by accessing windows, fans, blinds and doors seem to override any potential expectations of having conditions similar to AC zone. This implies that a building can be selectively air conditioned based on programmatic requirement or zone location (perimeter and core), while the other areas can be designed as a naturally ventilated building, and one still gets the benefits of adaptive comfort.

The higher temperature range for comfort in the NV zone also gives designers an opportunity to explore various passive design strategies in hot-dry climates that reduce indoor temperatures, which might not be far enough to meet the neutral temperature defined by the PMV based method. Studies evaluating the performance of passive design in hot-dry Indian climates, such as using passive downdraft cooling towers, have reported energy saving as high as 64% compared to air conditioned building (Ford et al., 1998), and a temperature reduction in the range of 12 ˚C – 14 ˚C. Other passive strategies that have been found to be effective are mud walls, thermal insulation over roof and nocturnal cooling (Ford et al., 1998, Chel and Tiwari, 2009, Nahar et al., 2003).

Although experiences in the AC zones did not seem to influence thermal expectations of occupants of the NV zone in our study, these results cannot necessarily be extended to a switchover type mixed mode building. The unanswered question in a switch over type MM building is - would installing an air conditioner influence the adaptive actions that occupants would have otherwise exercised, such as opening a window or turning on a fan?

Designers encounter two main challenges in a switchover type MM building. For a system that switches between NV and AC automatically, there does not seem to be a standard for deciding the temperature at which the switch over would happen. If the decision to switch on and off the air conditioner is left to the occupants, there is no certainty that occupants would actually turn off the air conditioner when the outdoor weather is suitable to open windows. Mutual consensus between occupants to turn off the air conditioner would also be a challenge.

In light of these difficulties, zoned type mixed modes have an advantage over switchover types. The energy saving in the unconditioned area is guaranteed and there are fewer concerns of HVAC control. Strategic location of programs within a building considering cooling requirements and appropriate use of passive design seems to be a promising way of reducing the cost of comfort in the 70% of the buildings that are yet to come up in India.

8. Conclusions
Overall, the mixed mode buildings are performing well in providing comfort in the hot and dry climate of Jaipur. Specific conclusions from this study are

- Indoor temperatures in the AC zone (23 – 29 ˚C) are much lower than the NV zone (29 – 36 ˚C) but occupants in the NV zone vote to be neutral or slightly warm in 71% of the observations and are comfortable during the significant majority of the times.
- Relative humidity in the NV zone ranged from 36 – 86% while in the AC zone it ranged between 31- 66%. In both zones, occupants rarely complained about feeling very humid.
- Fans were found to be turned on in 98% of the observations in the NV zone with high air speeds (mean = 0.9 m/s), indicating that occupants in prefer to have air movement.
- The comfort temperature range in which 80% of the people were satisfied was found to be 23 – 29 ˚C in the AC zone, compared to 29 – 34 ˚C in the NV zone.
- The ASHRAE Standard 55 adaptive model and the adaptive model developed by Madhavi et.al best modelled comfort in the NV zone of the MM buildings in a hot-dry climate.

- The opportunity to adapt to the warmer environments in the NV zone by use of windows, fan, blinds and doors overrides the possible increase in thermal expectation from intermittent exposure to AC zone.

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