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Sizing Natural Ventilation Systems for Cooling:
The potential of NV systems to deliver thermal comfort while reducing energy demands of multi-storey residential buildings in India.

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ABSTRACT: This paper aims to identify the potential of natural ventilation for cooling a representative two-bedroom residential apartment layout in India. India faces an unprecedented demand for residences and must reduce energy consumption associated with air-conditioning. Three significant climates and cities in India are investigated in this paper. The potential to extend the hours of the year for which thermal comfort is achievable using natural ventilation strategies is tested. This potential is identified by employing analytical methods to design and size ventilation capacity. Five natural ventilation design strategies are used over several scenarios varying window free area and ceiling fan speed. Indoor temperature setpoints are based on the India Model for Adaptive Comfort. Results are given as percentage of hours of the year for which natural ventilation is capable to remove calculated heat gains. Percentages of hours are divided into day-time and night-time. Findings show that the combination of large windows or balcony doors with additional ventilation openings and ceiling fan increases the total percentages of hours of the year for which natural ventilation is effective impacting on substantial energy consumption reduction with air-conditioning. Conversely, this potential varies with climate, and hence location.
KEYWORDS: Natural ventilation, Residential buildings, IMAC, Ceiling fan, Tropical climate

1. INTRODUCTION
The demand for residences in India will result in an increase of 400% in built area over the next three decades [1]. This demand will be fulfilled mostly with high-rise apartment blocks. Raise on income, growing expectation of thermal comfort and falling cost of air-conditioning (AC) systems will result in a record amount of AC being installed in residences in India: from 25 million now to 380 million in 2050 [2]. Energy consumption with AC will represent 45% of the total demand with buildings [3]. The development of high-rise residential buildings that are suitable for Indian climates and able to curb the energy consumption with AC has been considered of high priority for the Indian Government to tacke a future energy crisis. This is aligned with international efforts such as the Mission Innovation Project and the Advanced Cooling Challenge launched by the Clean Energy Ministerial.
Natural ventilation (NV) has the potential to improve thermal comfort while reducing energy consumption due to AC. This potential can be increased when NV is applied in conjunction with ceiling fans. Based on international collaborative research, this paper identifies the potential to expand the effectiveness of NV operating concurrently with ceiling fans for providing thermal comfort in residences in the challenging climates encountered in India. Three representative cities and climates in India are investigated. The potential of five NV design systems is identified using analytical methods [4,5]. Indoor temperatures are based on the India Model for Adaptive Comfort (IMAC) [6].

2. METHODOLOGY
The following steps were employed in this work: define climate thresholds and temperature set points for each climate investigated; identify the percentage of hours of the year suitable for NV in each location; define size of windows and ventilation openings in a two-bedroom apartment layout; assess the impact of ceiling fans on the thermal comfort sensation; calculate the required airflow rates to remove heat gains; and calculate to what extent five NV design strategies can supply the required airflow rates.

2.1 Climate thresholds and internal temperature
Weather data from the Indian Society of Heating Refrigeration and Air-conditioning Engineers (ISHRAE) [7] were used for the three cities and climates in India investigated: Ahmedabad (hot-dry), New-Delhi (composite), and Mumbai (warm-humid). The internal temperature (T_i) is defined using the IMAC for mixed-mode (MM) buildings, which operate as NV when temperatures allow and are assisted with mechanical devices when thermal comfort is not reached with NV alone. The IMAC-MM adaptive thermal comfort approach uses 30-day running mean outdoor temperatures ranging from 13°C to 38.5°C to calculate the neutral temperature ranging from 21.5°C to 28.7°C for these limits [6]. The algorithms calculate the

neutral temperature considering a ceiling fan to be operating at variable speed concurrently to NV. Here the IMAC-MM neutral temperature is considered as the initial T_i.

2.2 Hours of the year suitable for NV

The percentages of hours of the year for which climatic conditions allow NV for cooling to occur in each city is identified based on thresholds of relative humidity (RH) and air temperature. Firstly, weather data related to hours of the year were sorted for RH between 30% and 70%. Secondly, hours for which the inside to outside temperature difference results in negative values (outdoor > indoor temperature) were rejected, indicating that NV for cooling is not feasible. The remaining hours of the year were considered feasible to apply NV for cooling. The percentages calculated were then compared to percentages of hours for which NV is feasible from three adaptive thermal comfort models: IMAC-MM and IMAC-NV [6] and ASHRAE-55 [8] (Table 1).

Table 1: Percentages of hours for which NV is feasible as presented here and compared with reference models.

	Ahmedabad			New Delhi			Mumbai		
	day	night	**total**	day	night	**total**	day	night	**total**
MODEL	10%	21%	**31%**	12%	13%	**25%**	7%	9%	**16%**
IMAC MM			**34%**			**29%**			**27%**
IMAC NV			**21%**			**20%**			**27%**
ASHRAE 55			**20%**			**20%**			**16%**

2.3 Apartment layout and openings for ventilation

A two-bedroom residential apartment layout is used as case study (Fig. 1), as described in the GBPN Technical Report [1], which is based on a residential building design survey. Residential blocks with this layout will be widely built to meet the increasing demand for residences in India. These new buildings must be suitable for, and allow adaptations driven by the different Indian climates, as well as being environmentally and economically viable.

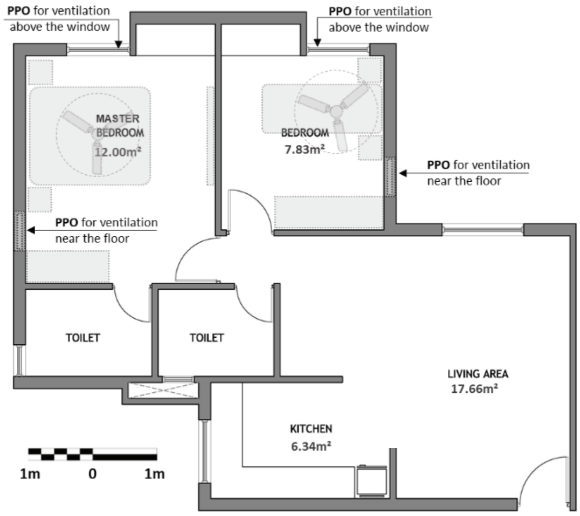

Figure 1: Apartment floorplan and cross-section [3].

The efficacy of two windows and a balcony door (Fig. 2) to provide ventilation for this apartment layout is tested. The width of these openings is kept as designed for the apartment: 1.0m. The horizontal sliding window type 'A' is commonly employed in recent buildings across India, but it provides a small opening free area (A_f). The double side-hung window type 'B' is an alternative to increase A_f by two times with the same frame size as 'A'. The type 'C' consists of a balcony door increasing A_f by three times. A pair of purpose provided openings (PPOs) [9] for ventilation was inserted in each bedroom (type 'D', also in fig. 2): one near the floor and the other near the ceiling to improve buoyancy. These PPOs should be placed in opposite or adjacent walls to allow wind-driven cross-ventilation. These PPOs are aimed to operate together with each of the three other types (A, B and C). Their efficacy was tested for some of the NV design scenarios (see section 2.6).

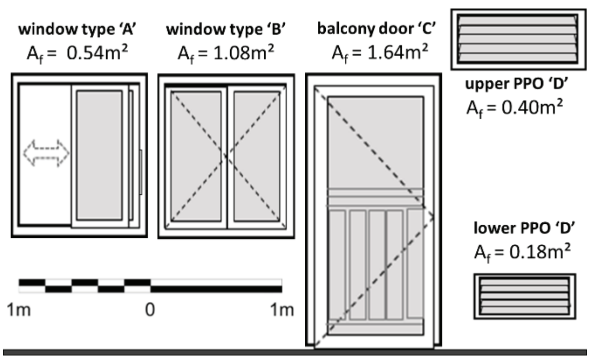

Figure 2: Schematic view of the openings for ventilation.

2.4 The impact of air velocity on the calculated T_i

Ceiling fans operating concurrently with NV have the capacity to keep thermal comfort sensations at increased temperature setpoints, thus reducing the overall time for which AC must operate. The increase in the air velocity allows a proportional rise in the T_i whilst maintaining thermal comfort [10,11,12]. This proportionality is calculated as an exponential trendline based on values from ASHRAE-55 [8] (Fig. 3). Based on Fig. 3 the T_i calculated via IMAC-MM is adjusted considering a ceiling fan operating at three speeds: 0.6m/s, 1.2m/s and 1.8m/s. While ASHRAE-55 indicates 1.5m/s as the limit for comfort in offices other authors report air velocities up to 2.0m/s as comfortable for residential environment [13,14,15].

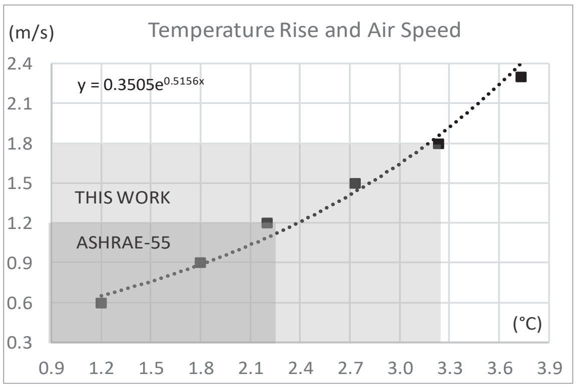

Figure 3: Relationship between temperature and air speed.

2.5 Required airflow rates to remove heat gains

Information about equipment density and occupant numbers [1] and metabolic rates [5] were used to calculate internal heat gains. Heat change with outside was obtained using Energy Plus dynamic thermal modelling software for a simplified construction modelled in Design Builder. After calculating the total heat balance, then airflow rates necessary for cooling were calculated [16,17].

2.6 Achievable airflow rates with five NV systems

The metric adopted to define the extent to which NV can be effective is the percentage of hours of the year for which the maximum achievable airflow rate with a given NV design system is either equal to or higher than the required airflow rate to remove the total heat gains. These NV systems are based on the guides CIBSE AM-10 [4] and CIBSE Guide A [5]. The NV design systems employed in this work are:

Single-sided ventilation, one opening (window or balcony door) buoyancy-driven

Cross ventilation, two or more openings (window or balcony door and PPOs) buoyancy-driven

Single-sided ventilation, one opening (window or balcony door) wind-driven

Cross-ventilation, two or more openings (window or balcony door and PPOs) wind-driven

Cross-ventilation, two or more openings (window or balcony door and PPOs) combined buoyancy and wind-driven

The capacity of each of these five NV design systems to provide the required airflow rates is tested based on the presented metric and applied for the two-bedroom apartment layout. The openings type A, B and C are assumed to be fully open. The PPOs type D are added in the NV design systems that make use of two or more openings for ventilation (the second, the forth and the fifth NV design systems), and are also assumed to be fully open, while in operation. Discharge coefficients (Cd) adopted for each of these openings are: for single-sided ventilation Cd= 0.25, for cross-ventilation Cd= 0.60, and for the PPOs with external louvres at 45° Cd= 0.32 [4,5,18,19,20].

3. RESULTS AND ANALYSIS

The results are displayed in this section in several charts. Percentages of hours are given for five NV scenarios separated for day-time, night-time and total time for the three cities and for openings type 'A', 'B' and 'C'. Figures 4, 5 and 6 show results for a ceiling fan operating at 0.6m/s; Figures 7, 8 and 9 for a ceiling fan at 1.2m/s; and Figures 10, 11 and 12 for a ceiling fan at 1.8m/s. All percentages hours are compared with benchmark percentage values obtained from reference methods: IMAC-NV, IMAC-MM and ASHRAE-55 (as previously shown in Table 1).

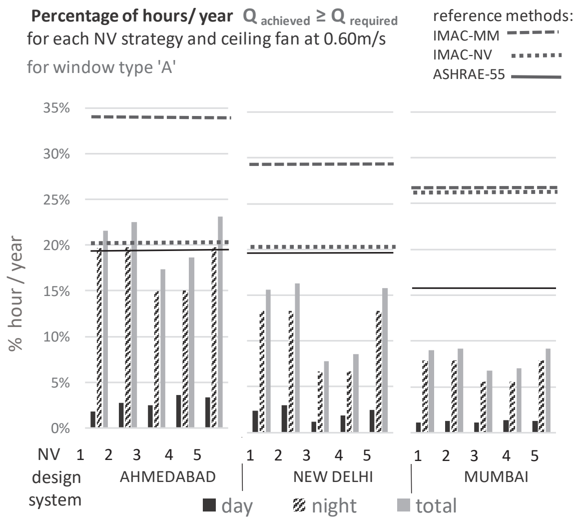

Figure 4: Results for scenario with window type 'A' and ceiling fan at 0.60m/s (initial scenario).

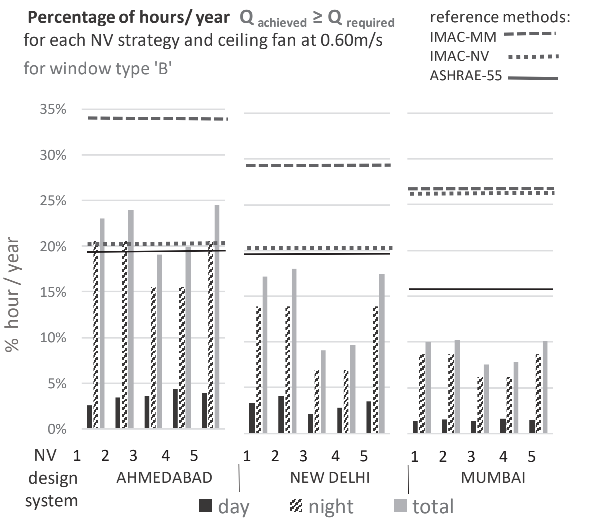

Figure 5: Results for scenario with window type ‘B’ and ceiling fan at 0.60m/s.

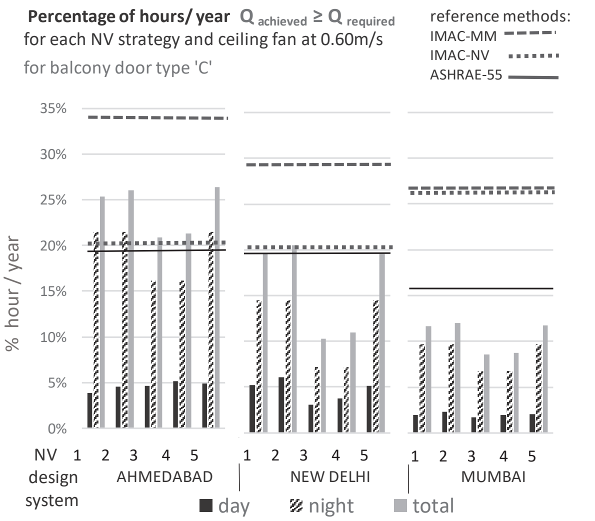

Figure 6: Results for scenario with balcony door type ‘C’ and ceiling fan at 0.60m/s.

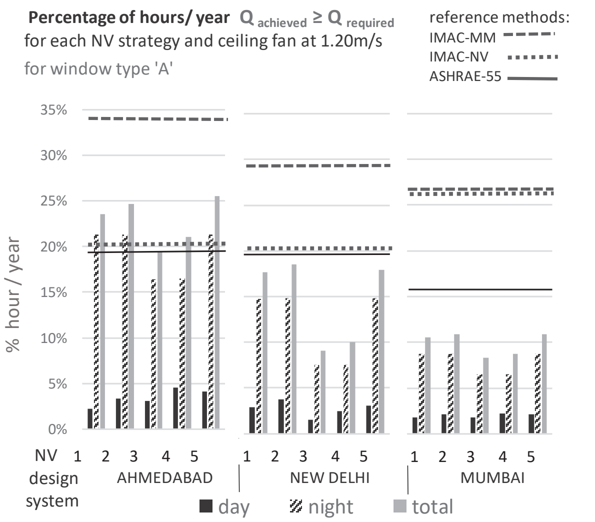

Figure 7: Results for scenario with window type ‘A’ and ceiling fan at 1.20m/s.

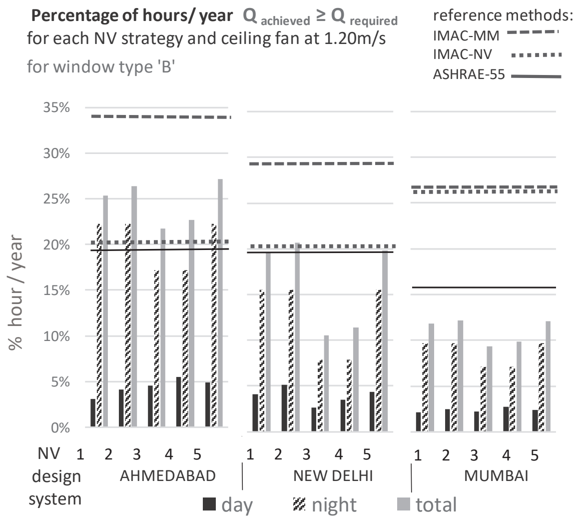

Figure 8: Results for scenario with window type ‘B’ and ceiling fan at 1.20m/s.

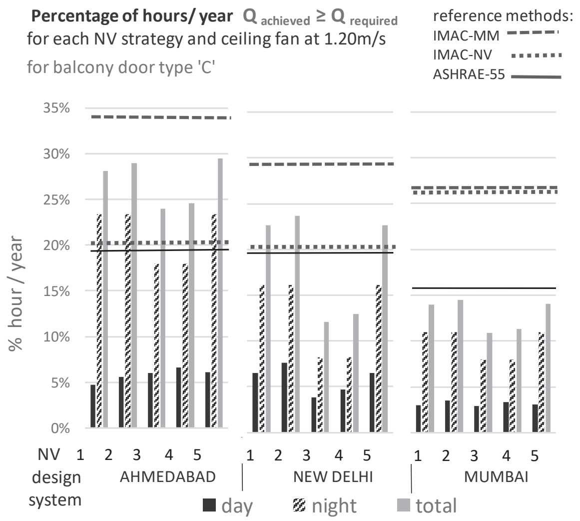

Figure 9: Results for scenario with balcony door type ‘C’ and ceiling fan at 1.20m/s.

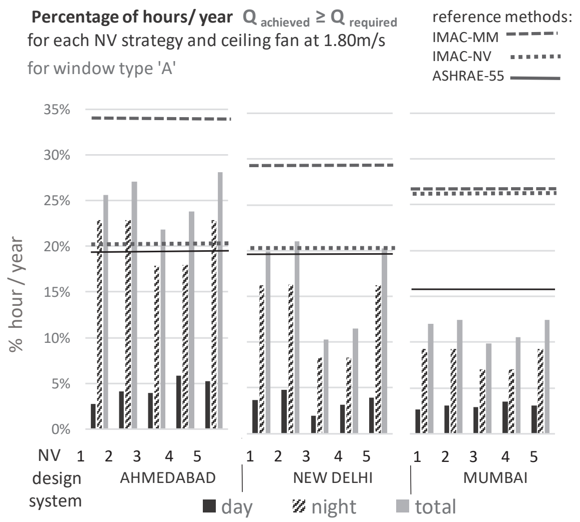

Figure 10: Results for scenario with window type ‘A’ and ceiling fan at 1.80m/s.

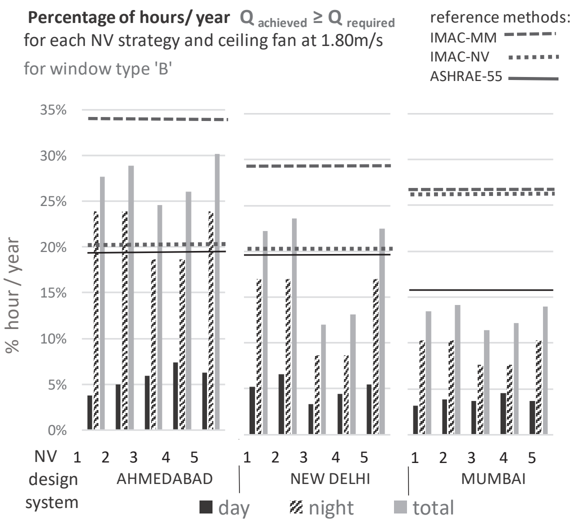

Figure 11: Results for scenario with window type 'B' and ceiling fan at 1.80m/s.

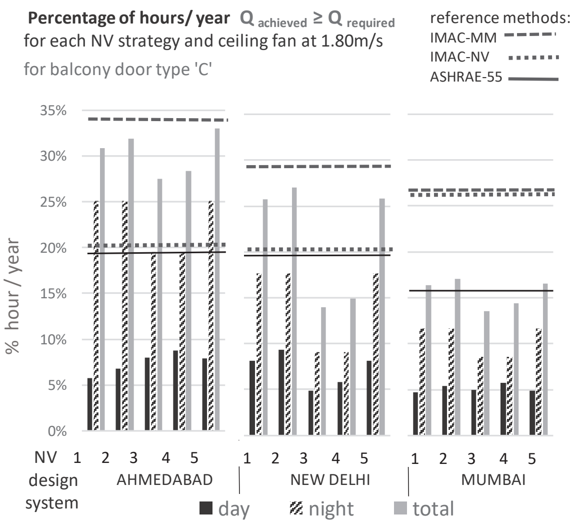

Figure 12: Results for scenario with balcony door type 'C' and ceiling fan at 1.80m/s.

3.1 Analysis of the potential for NV based on the climate of each city

The maximum percentages of hours of the year for which NV can provide thermal comfort range depending on the climate and location (see Table 1): Ahmedabad (hot-dry climate), with 31%, shows more potential for NV than New Delhi (composite), with 25%, which performs better than Mumbai (warm-humid), with 16%. Furthermore, NV occurs two times more during night-time than day-time in Ahmedabad (21% in contrast to 10%) and is more evenly distributed in New Delhi (13% in contrast to 12%) and Mumbai (9% in contrast to 7%). Reach or not these maximum percentages of hours for the two-bedroom apartment layout investigated will vary according to the NV system adopted, and it is not possible to declare a single strategy that meets all criteria for the three cities and climates analysed.

3.2 Analysis of the potential for NV based on the design system adopted for each city

For the five NV design systems employed, results from Fig. 4 to 12 show that, for the three climates and locations investigated, single-sided single-opening ventilation systems are less efficient than multiple openings which allow cross ventilation. This can be noticed comparing the results for the first and the second NV design systems or the third and the forth NV design systems. Cross-ventilation is achieved using the windows or the balcony door and the PPOs for ventilation in the bedrooms. Furthermore, for the three cities, buoyancy-driven ventilation is more efficient than wind-driven ventilation. This can be noticed comparing the results for the second and the fourth NV design systems. The fifth NV design system, which combines buoyancy and wind-driven ventilation, showed the best performance among the five options in all scenarios for Ahmedabad. Conversely, for New Delhi and Mumbai, results from the second and the fifth NV design systems are either practically the same or alternate the lead by a small difference according to the combination of the size of the openings and the ceiling fan speed.

Table 2: Percentages of hours for which NV is efficient considering buoyancy and wind-driven ventilation combined (fifth NV design system) and varying the opening type (A,B,C) and the ceiling fan speed (0.6, 1.2, 1.8m/s).

	AHMEDABAD			**NEW DELHI**			**MUMBAI**		
	0.6m/s	**1.2m/s**	**1.8m/s**	**0.6m/s**	**1.2m/s**	**1.8m/s**	**0.6m/s**	**1.2m/s**	**1.8m/s**
A	23.1%	25.5%	28.1%	15.8%	17.9%	20.2%	9.2%	10.9%	12.4%
B	24.5%	27.1%	30.1%	17.4%	19.8%	22.5%	10.1%	12.1%	14.0%
C	26.4%	29.5%	33.0%	19.6%	22.6%	25.8%	11.7%	14.1%	16.5%

Results of the total percentages of hours of the year for which NV for cooling can be employed for each of the cities varying the opening type/area (types A, B and C) and the ceiling fan speed (0.6, 1.2, 1.8m/s) are shown in Table 2. These results were obtained applying the fifth NV design system (buoyancy and wind-driven combined).

Increasing the free area of the opening type A by two times (type B) and then by three times (type C) allows a respective rise in the percentages of hours of 1.4% and 1.9% in Ahmedabad (total increase from using the opening type A to the opening type C of 3.3%), 1.6% and 2.2% in New Delhi (total of 3.8%), and 0.9% and 1.6% in Mumbai (total of 2.7%), when ceiling fans operates at low speed (0.6m/s). The same increase of the free area for ceiling fans operating at 1.8m/s causes the following rise in the percentages of hours: 2.0% and 2.9% in Ahmedabad, 2.3% and 3.3% in New Delhi, and 1.6% and 2.5% in Mumbai.

Conversely, larger glazed areas bring the disadvantage of increasing the heat gains during the hours of the year for which NV is not an option and, therefore, glass panels are closed. This situation is worsened for the façade receiving direct solar radiation. In this case, adopting windows with external louvered shutters could be an option to provide protection for glazed surfaces. Louvered shutters also allow NV to happen on rainy days when external temperature is within comfortable limits. A balcony or terrace (as in the solution presented as opening type C) also provides shading with the additional benefits of increased occupants' privacy, attenuate urban noise and create a buffer-zone between inside and outside.

Furthermore, the rise in air velocity from 0.6m/s to 1.2m/s and then from 1.2m/s to 1.8m/s increases respectively the percentages of hours for which NV can operate by 2.4% and 2.6% in Ahmedabad (total rise in the air velocity from 0.6m/s to 1.8m/s of 5.0%), 2.1% and 2.3% in New Delhi (total of 4.4%) and 1.7% and 1.5% in Mumbai (total of 3.2%) for openings type A. The same rise in air velocity will increase respectively the percentages of hours by 3.1% and 3.5% in Ahmedabad (6.6% in total), 3.0% and 3.2% in New Delhi (6.2% in total) and 2.4% and 2.5% in Mumbai (4.9% in total) with openings type C.

Finally, based on the results from Table 2, the greatest impact on the percentages of hours is observed when the increase on the free area of the openings are combined with rising fan speed. For example, comparing the results for the scenario with the opening size as designed for the apartment (type A: horizontal sliding window) and ceiling fan at 0.6m/s with a scenario combining the opening type B (double side-hung window) and ceiling fan at 1.2m/s and then with a scenario combining the opening type C (balcony door) and ceiling fan at 1.8m/s, the respective rise in the percentages of hours are: 4.0% and 5.9% in Ahmedabad (total impact on the percentages of hours of 9.9%), 4.0% and 6.0% in New Delhi (total of 10.0%), and 2.9% and 4.4% (total of 7.3%) in Mumbai.

4. CONCLUSIONS

This paper applies current engineering-based design methodologies to the case of a two-bedroom residential apartment of a design that will become widespread in India in coming years. The aim is to establish and increase the extent to which NV systems operating concurrently with ceiling fans can deliver thermally acceptable indoor conditions, thereby eliminating unnecessary use of air-conditioning at certain times. five NV design systems in three representative climates and cities in India were investigated. The main findings are as follows:

Windows sizes as currently designed for this apartment layout have limited capacity to deliver required airflow rates for cooling. Increasing typical sizes of windows free area by a factor of 3, combined the use of PPOs for ventilation and with ceiling fan usage, can rise the total number of hours in the year that NV can remove total heat gains by 9.9%, in Ahmedabad, 10.0% in New Delhi and 7.3% in Mumbai. Corresponding reductions in AC usage are: 36 days in Ahmedabad and New Delhi and 26 days in Mumbai, implying in substantial energy savings.

Whilst results are climate (location) dependent, they show the potential for improvement that can be achieved, even in some of the most challenging climates encountered across India.

The design changes envisaged for this apartment layout are considered both practical and feasible, and the analytical results reported here are due to be further analysed via dynamic thermal comfort model coupled with computational fluid dynamics and validated using a specially-constructed test facility at CEPT University, Ahmedabad, India.

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