Effectiveness of Ventilative Cooling Strategies in Hot and Dry and Temperate Climates of India

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ABSTRACT

Increasing use of air-conditioning in India is applying upward pressure on energy demand and may have implications on dependability. Electrical energy can be saved if favourable outdoor conditions are effectively utilized for cooling buildings with the minimum use of energy. This could be specifically applicable to residences where night-time use is more predominant for cooling by air conditioning systems but also aligns favourably with suitable outdoor conditions to be used as ventilative cooling. The potential of cooling with natural ventilation and mechanical ventilation remains an important topic to meet the needs of the larger section of the population who cannot afford to air-conditioning system as well as to reduce the energy consumption and greenhouse gas emission due to space cooling demands. This study evaluates the benefit of ventilative cooling techniques in Indian residences of hot and dry and temperate climates. The study first identifies typical residential plans in India based on past studies of residential surveys and existing literature. These plans are then simulated in DesignBuilder for modelling natural ventilation to understand baseline comfort and cooling needs. Further, ventilative cooling design strategies (single-side opening, cross-flow, stack ventilation with natural and mechanical ventilation) are designed using sizing methods described in IEA-Annex 62 and are incorporated in the residential plans to assess the ventilative cooling benefits. The effectiveness of ventilative cooling is investigated for two representative cities (Ahmedabad in hot and dry; Bangalore in temperate) located in two different climate zones of India to draw the comparison. The ventilative cooling benefits are quantified by percentage reduction in annual uncomfortable hours and cooling needs for various natural and mechanical ventilative cooling strategies in two the climate zones. Further, a novel method to continuously measure ventilation rate is developed for affordable yet accurate measurements. Short-term field measurements are conducted in an apartment building with continuous logging of surface temperatures, air temperature and air changes rates (using tracer gas method). The measurements are made to check if the input assumptions (such as ventilation rate or air velocity estimates) are realistic. These measurements are supported by physical model that calculates instantaneous ventilative cooling. The study provides scientific basis for building designers for incorporating ventilative cooling strategies. It also provides understanding of the benefits and limitations of natural and mechanical ventilative cooling in two different climates of India for residential application.

KEYWORDS

Ventilative Cooling, Field Measurements, Simulation, Natural Ventilation, Mechanical Ventilation

1 INTRODUCTION

Increasing use of air-conditioning in India is exerting upward pressure on energy demand and may have implications on reliability (McNeil & Letschert, 2010). There have been situations when power supply in many of the metropolitan cities of India is not able to meet the energy demand and causes a large number of hours of power cut off and shutdowns (Central Statistics Office, 2016). Electrical energy can be saved if favourable outdoor conditions are effectively utilized for cooling buildings with the minimum use of energy. This could be specifically applicable to residences where night-time use is more predominant for cooling by air conditioning systems but also aligns favourably with suitable outdoor conditions to be used as ventilative cooling. The potential of cooling with natural ventilation and mechanical ventilation remains an important topic to meet the needs of the larger section of the population who cannot afford to air-conditioning system as well as to reduce the energy consumption and greenhouse gas emission due to space cooling demands. The effectiveness of Ventilative cooling is dependent on the availability of suitable ambient conditions to provide cooling to the space and the comfort requirements.

2 LITERATURE REVIEW

Literature provides extensive guidance on theory, design and examples of ventilative cooling strategies (Axley, Emmerich, Dols, & Walton, 2002; Heiselberg, 2002; Jicha & Charvat, 2007; Kolokotroni & Heiselberg, 2015). Salcido et.al conducted an extensive literature review of the past work (1996-2016) on mixed-mode ventilation (Salcido, Raheem, & Issa, 2016). As shown in Figure 1, the study also documents percentage of energy saving potential by optimized window operation in mixed-mode buildings for various climate zones.

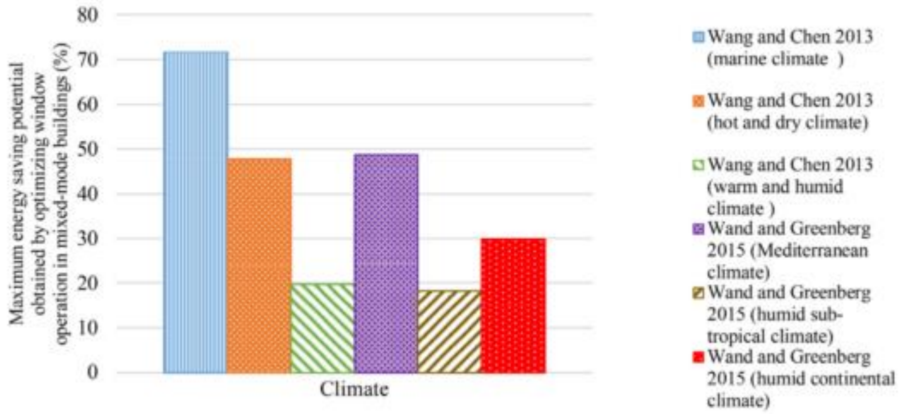

Figure 1: Overview of Research Methodology

Image Source: (Salcido et al., 2016)

Albadra and Lo (Albadra & Lo, 2014) performed short-term environmental monitoring and dynamic energy modeling of selected naturally ventilated domestic buildings in Lebanon and Jordan. Their initial results showed that computer modeling overestimates ventilation rates through windows with Venetian shutters. Aflaki et.al (Aflaki, Mahyuddin, & Baharum, 2016) demonstrated that the ventilation can vary a lot based on orientation and height. Both of these studies highlight the importance of field measurements of ventilation rates in buildings to avoid overestimation of ventilative cooling. Endurthy (Endurthy, 2011) studied in detail on how thermal mass can be coupled with night ventilation to maximize cooling benefits in the building and estimated about 12-13% reduction in electricity use can be achieved through night ventilation in Arizona.

Only a few studies have attempted to study free cooling benefits in buildings in India. Two studies have demonstrate good potential of free cooling and night purge in a commercial building in a temperate climate of Pune (Iddon & ParasuRaman, 2015; Thambidurai, Krishnamohan, Rajagopal, & Velraj, 2015). However, these studies looked at the potential of free cooling in a representative office building with air conditioning systems. Further, the study focused on a demonstration in a favorable climate and did not assess the benefits of different ventilative cooling strategies in the building.

Gradillas (Gradillas, 2015) studied the benefits of natural ventilative cooling in an 3 m by 3 m by 3 m cube located in Bhuj, Gujarat using DesignBuilder for single-side and cross ventilation strategies. However, the results are expected to be quite different for a complex residential building. Thomas (Thomas & Thomas, 2014) states that the significant energy savings potential can be achieved if the apartments in India are designed as per natural ventilation guidelines and principles mentioned in national building codes (NBC). While it provided suggestions on

possible natural ventilation strategies for a residential plan and suggested good potential of the same based on climate analysis, it has not simulated or calculated benefits of the approach.
This paper attempts to study the effectiveness of ventilative cooling in Indian residences first using simulation tools. Further, the study conducts periodic field measurement for one month in an apartment to compare the results with the simulation models.

3 METHODOLOGY

The approach of the study is to use the already available data of apartment typology in two climates of India, one which is considered favorable for ventilation (temperate) and one which is a harsh climate for ventilative cooling strategy (hot and dry). Simultaneously, conduct some actual measurement in hot and dry climate observe the difference to validate input assumptions for simulation models. Figure 2 shows the steps followed for simulation as well as measurement study.

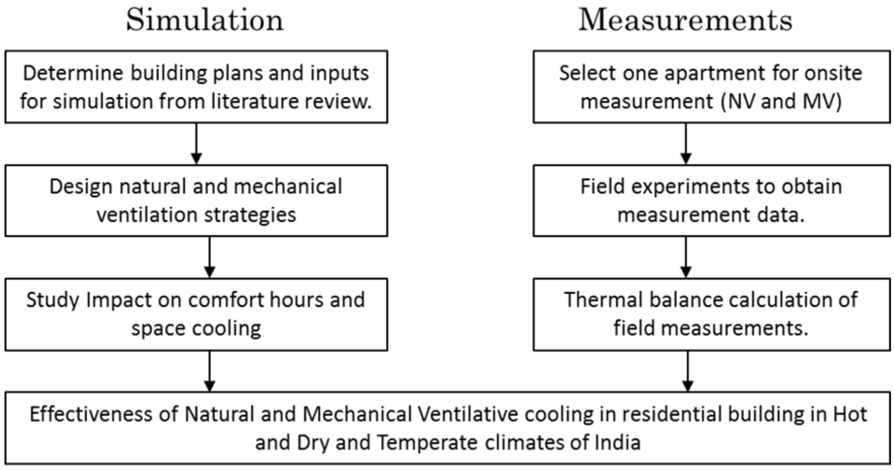

Figure 2: Overview of Research Methodology

3.1 Simulation Models

To assess ventilative cooling potential in India, the study needs to first identify typical residential plans and constructions in India. Rawal and Shukla (Rawal & Shukla, 2014) selected five typical apartment layouts based on a survey of existing building plans and modeled them in DesignBuilder to estimate energy consumption of a typical residential apartment. They also surveyed eight hundred (800) residences in India to develop appropriate inputs on equipment penetration and simulation inputs. Hence, one bedroom, two bedroom, and three bedroom floor plans identified in the above study is used to model typical residential building in order to estimate benefits of ventilative cooling.
The study also highlight that the Indian residences are designed for zoned mixed mode where an air conditioning system is typically installed only in the bedrooms. Further, the air-conditioning system in the bedroom operates in change-over mixed mode where the system runs only during extreme weather periods. Manu (Manu, Shukla, Rawal, Thomas, & Dear, 2016) developed adaptive comfort model suitable for mixed-mode buildings in India known as IMAC (India Model of Adaptive Comfort). This model is primarily developed for commercial building operated in mixed-mode operation. In the lack of a perfect comfort model for this residential study, the IMAC has been used for set points as it is developed for Indian context and is applicable for mixed-mode buildings. This comfort model has recently been integrated into the revised National Building Code. IMAC is used as comfort criteria for typical residences

in India to determine the number of uncomfortable hours and to use the set points to estimate the flow rate.
Table 1 provides key simulation inputs in simulation model. Ahmedabad location is selected under hot and dry climate and Bangalore is selected under the temperate climate.

Table 1: Key Simulation Inputs

Envelope Construction and Thermal Properties	
Wall	12mm Outside Plaster + 230 mm brick wall + 12 mm Inside Plaster U-Value - 1.722 W/m^2-K
Roof	10 mm Tiles + 12mm Plaster + 150 mm concrete roof + 12mm Plaster U-Value - 2.942 W/m^2-K
Window	Single Glazing with Aluminium Frame 22% Window to Wall Ratio (as per plan) U-Value - 5.8 W/m2-K, SHGC - 0.82, VLT – 0.8
Floor	10 mm Tiles +12mm Plaster + 150 mm concrete roof + 12mm Plaster U-Value - 2.942 W/m^2-K
Zone Area, Operation Schedule, Occupancy and Internal Heat Gains	
Bedroom	Operation: 10 pm to 7 am, Internal Gains (lighting + equipment): 320 Watts, Occupancy: 2 people, Area: 9.6 m^2
Living Area / Kitchen / Others	Operation: 7 am to 10 am and 7 pm – 10 pm, Internal Gains (lighting + equipment): 800 Watts, Occupancy: 2 people

The following natural and mechanical ventilative cooling strategies have been identified for evaluation in the simulation model (Figure 3):

- Natural ventilation - Single-side one opening, Cross-ventilation (openings in opposite direction of the room), Single-sided two openings, one on top of the other (stack)
- Mechanical Ventilation -Fan assisted cross-ventilation (openings in opposite directions), Fan assisted single sided two openings at different heights (stack)

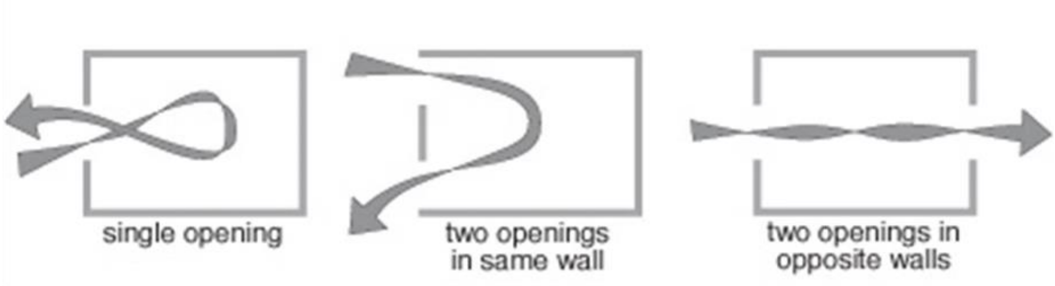

Figure 3: Sectional sketch of Ventilative Cooling Strategies

These ventilative cooling strategies are designed using sizing methods described in IEA-Annex 62 and are incorporated in the residential plans to assess the ventilative cooling benefits. The initial aim of the paper was to use Coolvent to estimate ventilative cooling benefits. However, Coolvent could not model the detailed plan of the residential buildings especially zoned mixed-mode configurations. Hence, the typical residential apartments are modelled in DesignBuilder V4.5.1.178 (Designbuilder, 2017). This tool has a user-friendly interface with capability of whole-building energy simulation, load calculation and natural ventilation mode simulation.

3.2 Field Measurements

Past literature emphasized the importance of field measurement to avoid overestimation of ventilation rates. Hence, this research incorporates air changes per hour (ACH) as one of the important measurements during field measurements. The approach devised for field measurement was a variant of the continuous tracer gas injection method (Persily, 2016; Sherman, 1990). But here, the measured sublimation rate of dry ice was used as a tracer gas source for generating CO2 inside the room. The intention was to be able to measure the continuous ventilation rates to quantify the ACH for calculation of the measured ventilative cooling effect.

An unoccupied two-bedroom apartment was selected for field measurements on the first floor (one floor above ground floor level) of an apartment complex. One bedroom with windows on East and South direction was the focus for monitoring purpose and was set up with measurement instruments to measure the ventilation rates (as explained below). Figure 4 shows the layout of the field measurement equipment at the monitoring site. The red dots represent the location of surface temperature sensors. The black dot represents the location of CO2 logger. The blue dot represents the location of the air temperature and humidity logger. There is a ceiling fan situated in the centre of the room, which is operated at a low speed throughout the measurement period for proper mixing of the air inside the room.

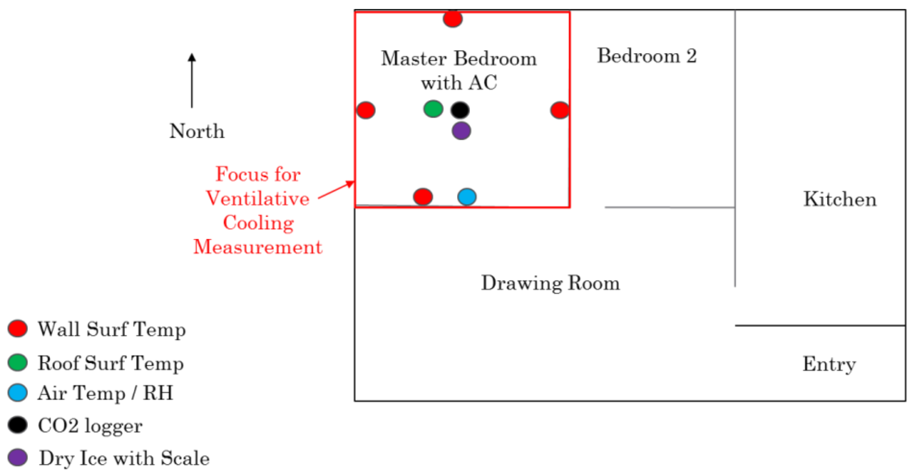

Figure 4: Apartment layout of field measurement

During field measurements of ventilative cooling, an important parameter to monitor in building is ventilation rate. A block of dry ice of around 10 kg is placed in an insulated box on a precision electronic weighing scale in the centre of the room and allowed to slowly release carbon dioxide (CO2) in the space. More dry ice is added daily to keep continuous generation. The weighing scale is connected to a laptop placed at the site and is given command though a Python code to continuously log the weight of the dry ice at 5 minutes' intervals. Concurrently, to measure the CO2 concentration inside the space, a calibrated HOBO MX 1102 logger is used (Onset, 2017) to continuously measure and store CO2 levels in the space every 5 minutes. Once the CO2 source strength (mass of dry ice sublimated into gaseous CO2) and the well-mixed indoor CO2 concentration are measured, it is possible to calculate the air exchange rate using a mass balance model. The continuous ventilation rates are calculated for each measurement period using the mathematical expression for change in mass concentration of indoor CO2 (Traynor, Aceti, Apte, Smith, & Green, 1989).

The inside surface temperatures of the six surfaces (four walls, floor and ceiling) were measured using thermistors in a circuit made with the help of Arduino Uno board (Arduino, 2017). The temperature data were recorded continuously for every time step of 5 minutes as per the code

uploaded in the board, and were stored in the memory card inserted in the Arduino circuit board. Outdoor weather data were obtained from online website (WorldWeatherOnline, 2017).
Simplified room thermal balance is used to understand the effectiveness of ventilative cooling in the monitored space. This calculation provides the difference in the temperature achieved with taking into consideration all the components adding to or removing the heat from the space. The field measurements were carried out in an unoccupied apartment; hence occupant gain was nil. Lighting, and equipment details were noted down from onsite visits and the cooling loads caused by them are calculated using 2009 ASHRAE fundamentals (American Society of Heating, Refigerating, and Air Conditioning Engineers, 2009). Similarly, construction details of wall, roof, floor, and window were obtained for the measured apartment to calculate area, specific heat, and thermal conductivity of each envelope components.

4 RESULTS AND DISCUSSIONS

4.1 Simulation Results

The simulation results generated from the Design Builder software for the apartment models created for the study are compared using two metrics – uncomfortable hours and reduction in thermal cooling needs of the space. The simulation results are compared using the operation model described in Figure 5.

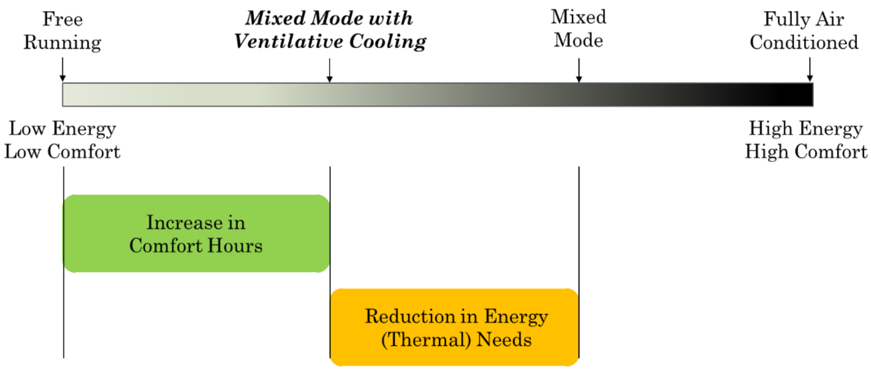

Figure 5: Parameters to quantify cooling benefits for various modes

As seen in Table 2, natural (NV) and mechanical ventilation (MV) can reduce annual uncomfortable hours by 10-12% and 21-40%, respectively, as compared to free-running mode.

Table 2: Percentage Reduction in Annual Comfortable Hours

% Reduction in annual discomfort Hours	Ahmedabad			Bangalore		
	1BHK	2BHK	3BHK	1BHK	2BHK	3BHK
Free Running	0%	0%	0%	0%	0%	0%
NV - Single Sided (One Opening)	5%	5%	6%	7%	7%	8%
NV - Cross Ventilation	14%	16%	13%	26%	11%	37%
NV - Single Sided (Two Openings- Stack)	12%	13%	10%	19%	8%	24%
MV - Fan Assisted Cross Ventilation	19%	21%	19%	27%	17%	35%
MV - Single Sided (Two Openings- Stack)	21%	23%	22%	28%	22%	43%

The ventilative cooling benefits are 2-10% higher in temperate climate as compared with hot and dry climate. The ventilative cooling benefits are slightly higher (3-5%) for cross-ventilation as compared to the single-sided ventilation.

Table 3: Percentage Reduction in Annual Thermal Cooling (kWh)

% Reduction in Thermal Cooling (kWh)	Ahmedabad			Bangalore		
	1BHK	2BHK	3BHK	1BHK	2BHK	3BHK
MM (No Ventilative Cooling)	0%	0%	0%	0%	0%	0%
NV - Single Sided (One Opening)	5%	4%	4%	7%	3%	5%
NV - Cross Ventilation	12%	12%	9%	14%	13%	12%
NV - Single Sided (Two Openings- Stack)	8%	9%	7%	13%	14%	10%
MV - Fan Assisted Cross Ventilation	29%	30%	27%	30%	27%	24%
MV - Single Sided (Two Openings- Stack)	31%	34%	30%	33%	31%	28%

4.2 Field Measurement Results

The measurements were done for a period of 30 days in the month of March and April. Data were recorded for three modes; free running, natural ventilation, and mechanical (fan-assisted) ventilation in random order during the course of measurement period. As explained in the methodology section, dry ice weight and CO_2 level are continuously measured in the room during field measurements. As an example, Figure 6 shows measured dry ice weight and CO2 measurements for 25th – 26th March. Each dot in the figure shows measured value at every five-minute sampling interval. The total measurement period shown in the figure is approximately 11 hours (129 measurements at every five-minute intervals). As seen in the figure, CO_2 level (ppm) in the space increased from 480 to 2100 ppm. During the same period, dry ice weight reduced by 500 grams (from 6.4 to 5.9 Kilograms) during the measurements period. The dry ice weight in the graph also shows inherent noises due to scale accuracy and limitations of the manual measurement approach. Hence, to filter the noises and to find a mean dry weight for the measurements period for further calculations, the measurements were fit with exponential curve fit. Very good fit was obtained ($R^2 > 0.95$) with exponential curve indicating the average weight change on scale are captured appropriately with exponential curve fit.

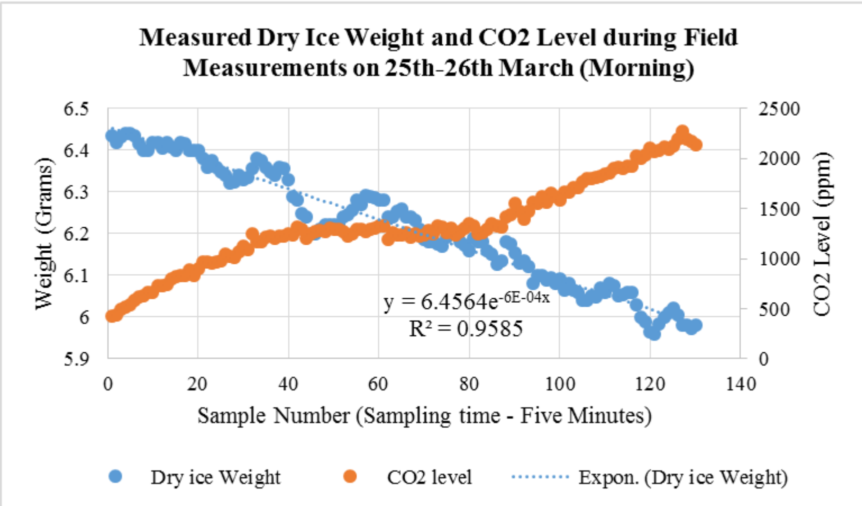

Figure 6: Measured CO_2, dry ice weight

ACH values were calculated from the data collected for CO2 ppm and dry ice weight. Figure 7 shows the summary of the entire measurement period of the ventilation rates observed in different modes of window operation. As can be seen Figure 7, the closed window mode or the free running mode where there is no natural ventilation happening, the air change as a result of infiltration shows the values of 0 to 2 ACH with the average value of 1 ACH. In the natural ventilation mode when the windows are open from morning to evening, the ACH values varies between 2.5 to 25 ACH and the average value is observed to be 5 to 7 ACH.

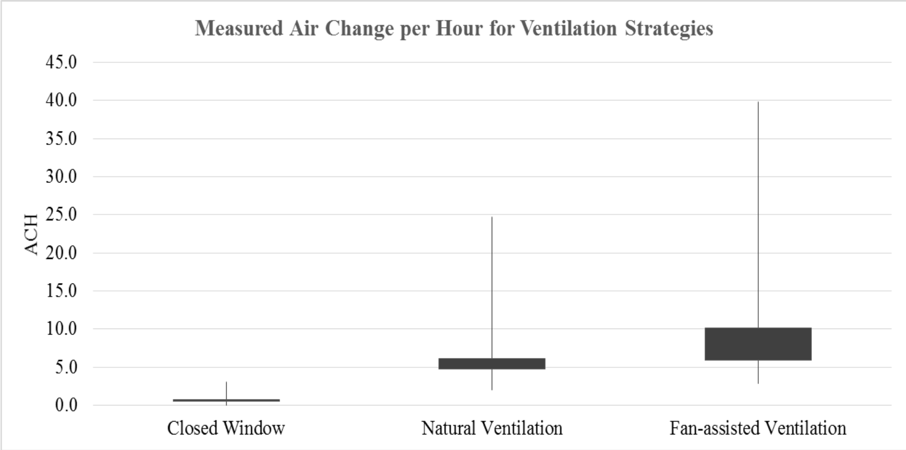

Figure 7: Summary of ACH in Different Window Operation Mode

For the fan-assisted mode, where a fan is kept on inside of the open window, the ACH values vary between 3 ACH to 40 ACH sometimes with an average value observed to be around 6-10 ACH. Once ACH is calculated, mass balance using air flow and temperature difference of indoor air and outdoor is used to calculate heat gain (heating) or heat loss (cooling) through ventilation.

Table 4: Summary of Ventilative Cooling during Field Measurements

Date	Minutes	Count	Cooling Needs (Watts)			Ventilative Cooling (Watts)			%Ventilative Cooling Possible			Operation Mode
			Average	Max	Min	Average	Max	Min	Average	Max	Min	
22nd Mar	85	17	101	158	69	-9	6	-50	10%	71%	-9%	Closed Window
23rd mar	270	54	221	342	144	17	64	-10	-7%	7%	-19%	Closed Window
25th Mar	725	145	366	472	134	51	291	-125	-13%	30%	-72%	Closed Window
26th Mar	1370	274	271	534	32	220	2924	-95	-51%	100%	-100%	Closed Window
28th Mar	130	26	-85	0	-131	2	10	-9	4%	23%	-7%	Closed Window
29th Mar	745	149	-4	310	-212	-3	143	-84	-37%	100%	-100%	Closed Window
2nd Apr	830	166	396	483	185	65	471	-43	-16%	9%	-100%	Closed Window
17th Apr	1440	288	361	582	113	-24	459	-785	10%	100%	-96%	Closed Window
24th Mar	115	23	112	139	77	-125	-8	-405	100%	100%	6%	Open Window
26th Mar	1370	274	271	534	32	220	2924	-95	-51%	100%	-100%	Open Window
27th Mar	370	74	157	245	75	78	5728	-1090	21%	100%	-100%	Open Window
3rd Apr	1415	283	283	503	35	-18	519	-474	22%	100%	-100%	Open Window
4th Apr	1410	282	283	442	91	4988	97801	-315	-100%	100%	-100%	Open Window
7th Apr	145	29	152	180	117	-22	75	-152	18%	100%	-45%	Open Window
8th Apr	1440	288	268	450	38	367	3294	-432	-37%	100%	-100%	Open Window
9th Apr	835	167	240	573	41	121	2183	-550	76%	100%	-100%	Open Window
20th Apr	55	207	239	495	9	582	13649	-29542	100%	100%	-100%	Open Window
12th Apr	130	26	113	213	38	159	854	-53	-100%	38%	-100%	Open Window and Fan
13th Apr	1420	284	-1	131	-140	721	52599	-2663	-100%	100%	-100%	Open Window and Fan
14th Apr	885	177	-24	161	-219	1731	56475	-712	-100%	100%	-100%	Open Window and Fan
15th Apr	655	131	513	610	278	-1142	29047	-33529	100%	100%	-100%	Open Window and Fan
16th Apr	1430	286	341	570	34	63	6103	-2081	100%	100%	-100%	Open Window and Fan
17th Apr	1440	288	361	582	113	-24	459	-785	10%	100%	-96%	Open Window and Fan
18th Apr	145	29	216	317	147	70	3586	-2174	-22%	100%	-100%	Open Window and Fan
19th Apr	1440	288	235	449	-5	295	4238	-1195	100%	100%	-100%	Open Window and Fan
20th Apr	1035	207	239	495	9	582	13649	-29542	100%	100%	-100%	Open Window and Fan

Table 4 shows the calculated amount of cooling load (watts) requirement for the monitoring space through heat balance equation. It also shows the ventilative cooling contribution in watts and percentage as average, maximum and minimum value for each day of measurement. Further, using the inside surface temperature and air temperature measurements, a simplified room thermal balance is used to understand the effectiveness of ventilative cooling in the monitored space. The cooling ventilative cooling benefits are classified in 0-25%, 25-50%, 50-75%, >75% benefits throughout the measurement periods. Since the window is at one position, negative benefits are also achieved when outdoor conditions are not favourable. Table 5 provide summary of ventilative cooling benefits during the field measurements.

Table 5: Measured Ventilative Cooling Benefits

	Closed Window		Natural Ventilation		Fan Assisted Ventilation	
	Hours	% Monitored Hours	Hours	% Monitored Hours	Hours	% Monitored Hours
Not Measured	395		320		293	
0-25% Cooling Benefit	70	19%	60	11%	44	8%
25-50% Cooling Benefit	24	6%	39	7%	22	4%
50-75% Cooling Benefit	12	3%	16	3%	12	2%
>75% Cooling Benefit	3	1%	117	22%	128	22%
Negative Benefits	264	71%	312	57%	365	64%
Total Hours	768		864		864	
Outdoor Air Temperature (deg C) - Only during Monitored Hours						
Max	43		44		45	
Min	27		25		28	
Average	35.7		34.8		36.8	
Standard Deviation	0.5		0.52		0.55	

The period where ventilative cooling can meet more than 75% of space cooling needs increases from 1% in closed window (infiltration only) to 22% in natural and mechanical ventilation modes. Outdoor conditions during the monitoring period is similar between the three operation modes with slightly higher outdoor temperature during open mechanical (fan-assisted) ventilation modes. Natural and mechanical ventilation strategies performed very similar during the monitoring period.

5 CONCLUSIONS

The simulation results demonstrate good potential for natural and mechanical ventilation strategies to be effective for apartment residences in India. Adding ventilating cooling using natural ventilation in a typical residential apartment provides 5-43% increase in comfortable hours for two climate zones of India as compared with free running building. Ventilative cooling with mechanical ventilation provides significant comfort benefits (14-25% as compared to ventilative cooling with natural ventilation) and is beneficial to incorporate in residential apartment buildings. When compared to mixed mode buildings with no ventilative cooling, ventilative cooling can reduce thermal load of the apartment by 4-14% and 24-34%. While ventilative cooling is more effective in temperate climate, significant benefits can be achieved even in hot and dry climate of India during night periods. A novel method to continuously measure ventilation rate is developed for affordable yet accurate measurements. The measurements are performed for one month in a bedroom of apartment building where air change per hour and ventilative cooling benefits are calculated for one bedroom. The finding indicates significant savings benefits for natural and mechanical ventilation. Unlike simulation, the benefits measured in field indicated similar benefits between natural and mechanical ventilation. This could be due to slightly worse outdoor conditions during mechanical ventilation measurements or due to underestimation / overestimation of natural and mechanical ventilation savings in simulation models.

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