A CASE STUDY ON DESIGN OF THERMALLY COMFORTABLE AFFORDABLE HOUSING IN COMPOSITE CLIMATE: SIMULATION RESULTS & MONITORED PERFORMANCE

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ABSTRACT

New urban housing in India is heavily focused on construction of affordable housing (housing for families belonging to low- and medium-income groups). The design of the new affordable housing should ensure acceptable level of thermal comfort for the occupants without the use of air-conditioning, which majority of the occupants are unable to afford. Thus, proper design of building envelope to control heat ingress and allow adequate ventilation becomes critically important.

The paper presents a case-study of integrating energy efficient envelope and ventilation strategies in a PMAY affordable housing project at Rajkot (composite climate). The project consisted of 1176 dwelling units, each of 33.6 m^2 built-up area. The measures to reduce heat ingress included low U-value walls, shading of windows and partly opaque window shutters. For ventilation, adequately sized casement windows were provided. Building energy simulations (using *EnergyPlus 8.3*) were carried out. After construction, indoor temperatures (air and wall) and natural ventilation were monitored in selected unoccupied flats during the summer of 2019.

The paper presents the design strategies along with energy simulation and monitored results. Maximum average indoor air temperature of 32°C was recorded in the sample unoccupied flat (with proper window opening and closing schedule) during the monitoring period (maximum average ambient temperature of 39°C). The monitored indoor temperatures show good correspndance with the simulated results.

Keywords—Thermal comfort, Affordable housing, Passive design, Performance monitoring

INTRODUCTION

The Pradhan Mantri Awas Yojana (PMAY)- Housing for All (Urban) is Government of India's flagship programme to fulfil the housing demand / housing shortage for the urban poor. This mission target is 12 million affordable houses between 2015-2022, which will be provided central financial assistance / subsidies through the states / UTs with different implementing mechanisms. The targeted construction is almost 11% of the predicted urban residential built-up area, which will house 20-30% of the urban population in 2022 [1].

Heat gains from the building envelope (external walls, windows, roof) play the most significant role in influencing thermal comfort and consequently energy efficiency in residential buildings. Residential buildings have large exposed façade area to built-up area ratio, resulting in the space cooling loads dominated by heat gains from the envelope. The penetration of air-conditioners in residential buildings is low, more so in affordable housing. Thus, design of the building envelope to control heat gains and allow adequate ventilation become vital in maintaining thermal comfort.

The paper presents a case-study of integrating energy efficient envelope and ventilation strategies in a PMAY affordable housing project at Rajkot (composite climate). The project consists of 1176 dwelling units, each of 33.6 m^2 built-up area (**Figure-1**). These flats were designed in 11 towers of 7 storeys with stilt parking (S+7). In 2016, a design workshop was conducted for this project to make it thermally comfortable and energy efficient. The following envelope and ventilation measures were recommended:

- External walls with low U-value
  - 200mm thick Aearted Autoclaved Concrete (AAC) blocks on the east and north side.
  - Cavity wall, constructed of 200mm +200mm thick AAC blocks with 40mm air gap on the south and west sides
- Partially glazed windows
- Window shading (with overhang and side-fins)
- Casement windows were provided, instead of sliding windows, to improve natural ventilation potential
- A common assisted ventilation system was provided to improve ventilation through the flats in case of low wind-speeds. The test results presented in this paper does not include the performance of this system.

Building energy simulations (using *EnergyPlus 8.3*) were carried out to estimate the impact of these measures on internal temperatures.

The project completed construction in early 2019. In May 2019, indoor temperatures and natural ventilation were monitored in selected unoccupied flats.

The results of the above monitoring and the energy simulation are presented, with the focus on impact of the building envelope measures.

MONITORING METHODOLOGY

Monitoring objective

The main objective of the monitoring exercise was to measure the impact of the building envelope strategies and natural ventilation on the internal temperatures of the flats, during peak summer season, and compare it with the simulation results.

Monitoring period

The test was planned to be carried out during a period when the maximum temperature would be consistently above 40°C. Temperature data of the summer months for the last four years (2014-2018) was checked to find this "hot" period. The period between 15th April and 31st May was found conducive, and the test was conducted between 5th May to 31st May 2019.

Selection of the test flat

The test flat was was on 4th floor and faced north (**Figure-1** & **Figure-2).** This flat was chosen for the following reasons:

- It is on an intermediate floor, with windows and opening over north side.
- The general wind direction on the site is from the west. The test flat should be one which does not have direct or "first" access to the wind.

Parameters measured

Table 1 showes the parameters that were measured and the measuring equipment.

Table 1: Details of monitored parameters, instruments and their locations

PARAMETER	INSTRUMENT	LOCATION
Ambient		
Ambient DBT & RH	Rotronic XD-33 Temp+Humi Sensor Transmitter with Weather Shield	Terrace; above the overhead water tank (OHT)
Roof-top wind speed	Wind Speed sensor (WIND-COMBO-1)	Terrace; above OHT
Roof-top wind direction	Wind Direction Sensor (Wind vane type potentiometer)	Terrace; above OHT
Indoor		
Bedroom and living room DBT & RH	Rotronic XD-33 Temp+Humi Sensor Transmitter	Centre of the room
Bedroom and Living room CO2 concentration	E-sense CO2 sensor	Centre of the room

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Figure 1: Site plan showing the location of the test flat

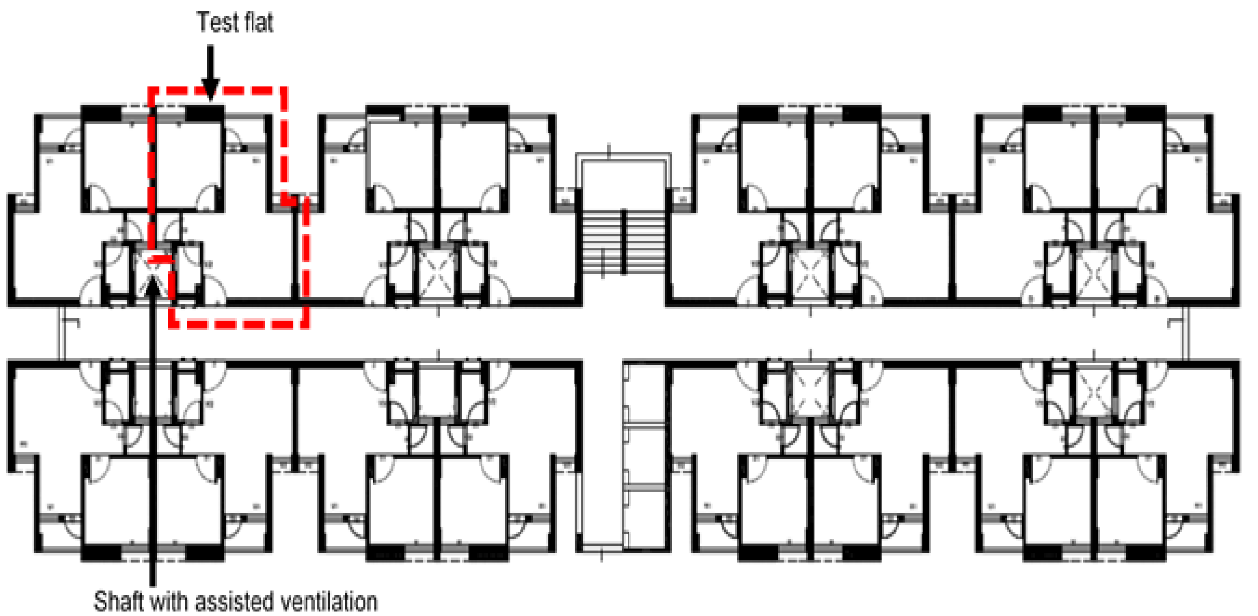

Figure 2: Floor plan of the block with the test flat

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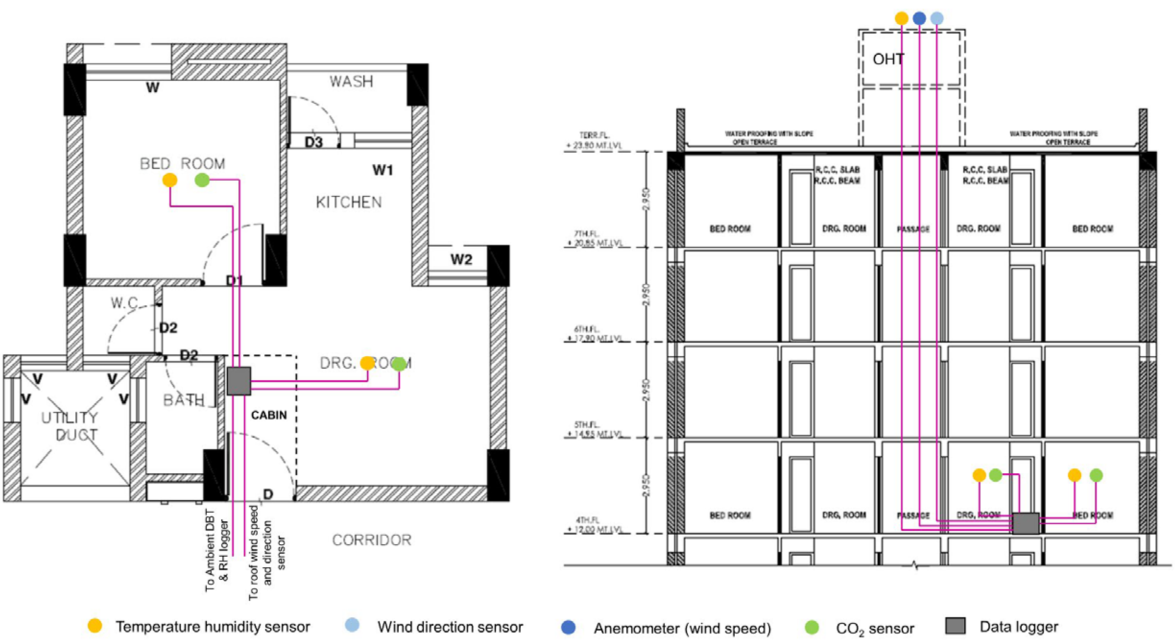

Figure 3: Plan and section of the test flat showing location of sensors and loggers

A 16-channel data logger (SMART SCAN 16 Sunsui Make Universal Input Data Logger with GSM / GPRS) was used to log the above parameters. Frequency of logging was 1 minute. Two ceiling fans in the centre of the bedroom and living room were operated at low speed throughout the measurement period for proper mixing of air.

Test set-up and operation

Figure-3 shows the layout of the equipment. All sensors were connected to the 16-channel logger for continuous logging. A laptop was connected to the logger for display and check. A temporary cabin was installed (**Figure-3**) as an observation area with the laptop and data logger. This cabin isolated the experimental area allowing general observation and scheduled data retrieval without impacting the experimental reading due to presence of human body, CO_2 exhaled by the observers and sudden air-exchange while opening the door.

Continuous logging of all parameters was carried out. The openings were operated as follows:

- The windows of the bedroom (W) and living room (W2) were closed during the day (8 am to 8 pm) and opened at night.
- The entrance door of the flat (D), opening into the corridor, was closed at all times. The louvred opening above this door was also sealed.
- Kitchen window (W3) and wash door (D3) were closed at all times.
- The doors to the WC (D2) and bathroom (D2) were closed. The louvred opening above these 2 doors were kept open.
- The door between bedroom and living room (D1) was kept open at all times.
- The windows of this flat were equipped with mosquito nets.

Calculation of Air Change per Hour (ACH) by constant injection technique

The constant injection technique uses a tracer gas introduced into a room / space at a constant rate and measuring the resulting tracer concentration. The tracer gas used in this case was CO_2 for cost effectiveness, easy availability and for easy replicability of this test in other houses. A constant flow of CO_2 (3.6 NLPM) was injected into the space. In this case, the entire flat, excluding the WC and bath, was considered as one space.

CO_2 sensors placed in the bedroom and living room measured and logged the CO_2 concentration. Average ACH values were calculated for the day (windows closed) and night (windows open), using the following equation [2]:

$$\bar{Q} = (\overline{\frac{Q_T}{C}}) - \frac{V}{\Delta t}\log_e\left(\frac{C_{final}}{C_{initial}}\right) \quad (1)$$

CO_2 concentration over and above the average ambient concentration of 350 ppm was used in the equation above.

SIMULATION MODEL

To validate the monitored data, computer simulation was done for the period from May 12, 2019 to May 22, 2019. The software used for the simulation was - *DesignBuilder 4.7*, which does energy calculations using *EnergyPlus 8.3* simulation engine. The following are the main modelling inputs required for the computer simulation:

- To simulate the vacant monitored flat, the input for occupancy schedule is given as '*off*' for the simulation period.
- The ISHRAE weather data file of the test site was customized for the simulation period using a open-source tool called '*Elements*' and the resultant output file was taken as input weather data file for simulation.
- Window openings are modelled as partial glass and partial PVC as per the actual sizes. Thermal, visible and solar properties of single-glaze glass are taken as given in the in-built property library of the software while for PVC, the following are the values of the properties given as input [3,4]:
  a) Thermal conductivity = 0.19 W/m-K
  b) Outside solar reflectance = 0.8
- To model the recessed window of the bedroom in the simulation tool, a '*reveal outside depth*' of 0.53m (as per the drawing) is given as an input.
- Thermophysical properties of the walling material (AAC) was taken from the in-built property library of the simulation software.
- To model the forced convection due to ceiling fan (28W) running continuously for the monitored period, the convective heat transfer coefficient for internal wall surfaces is taken as 15 W/m^2-K
- Natural ventilation through the flat (except WC & bathroom and corridor) is modelled by using the measured hourly air change (ACH) rate data.

RESULTS

Monitoring results

a) Indoor temperature

- Indoor temperature for the bedroom goes up to a maximum average of 32.7°C during the day and minimum average of 30.6°C early morning (**Figure-4**) . The maximum average ambient temperature was 39.3°C, while the average minimum ambient temperature was 27.8 ºC. Thus compared to the diurnal varaiation of 11.5 ºC in the ambient temperatures, the diurnal varaition in indoor temperature was only 2.1 ºC. For the present study, the Indian Model for Adaptive Comfort (IMAC) is chosen as the thermal comfort model [5,6]. As seen in **Figure-**4, all hours of the monitored period falls within the 80% acceptability limits whereas 87% of the monitored period falls within the 90% acceptability limits.

b) Air change rate

- Variation of carbon dioxide concentration inside the flat for a representative day is shown in **Figure-5**. The measured concentration of CO_2 was used to measure average air change rate (ACH) inside the flat using **Equation-1**.
- From the measured CO_2 data (corresponding to the duration of computer simulation), the average ACH calculated for the daytime (closed windows) was 6.8h^{-1} whereas for the nighttime (open windows) the average ACH was 23.41h^{-1}.
- The window design ensures an average ACH of 23h^{-1} when they are open, through natural ventilation itself, which indicates very good cooling potential. This is enabled by the good wind speed available on-site and the accessibility to this wind through the windows of this flat.

Simulation results

- **Figure-6** shows the comparison of the measured and simulated temperature data of the bedroom inside temperature. To check the congruity between the measured and simulated data, Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were calculated for the dataset [7]. The temperature data from the simulated model matched the measured temperature data very well with MBE = -0.09, RMSE = 0.7 and an absolute average deviation of 0.6°C.

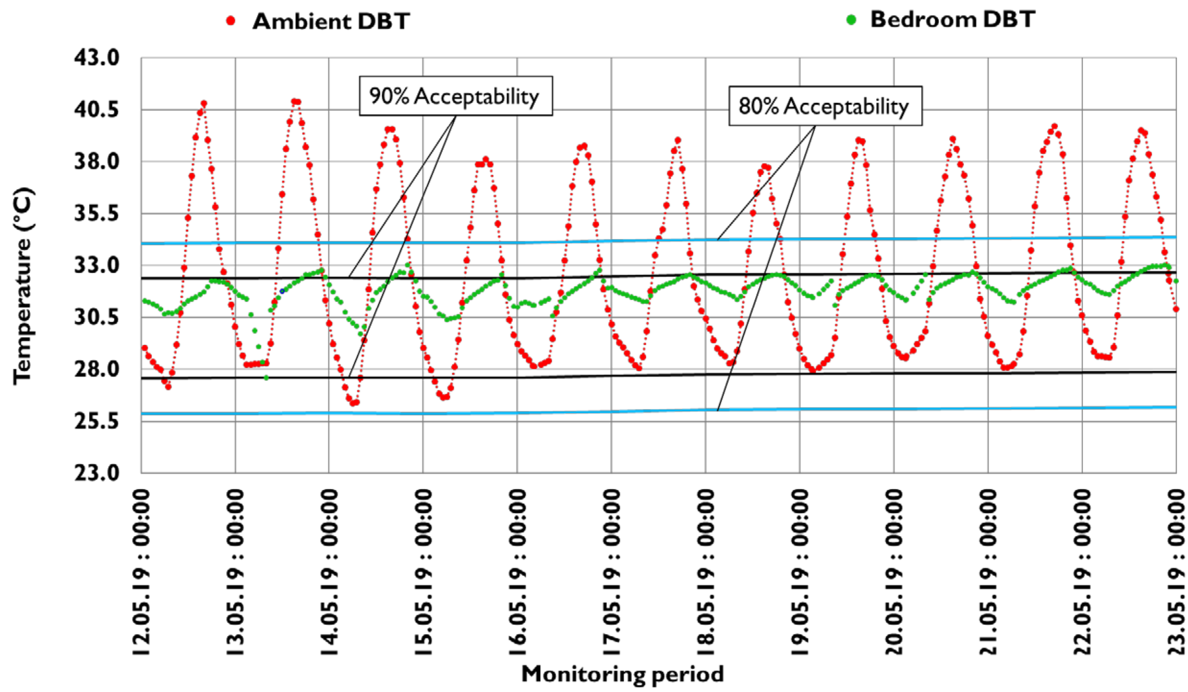

Figure 4: Graph showing monitored ambient temperature and temperatures inside the test flat (bedroom)

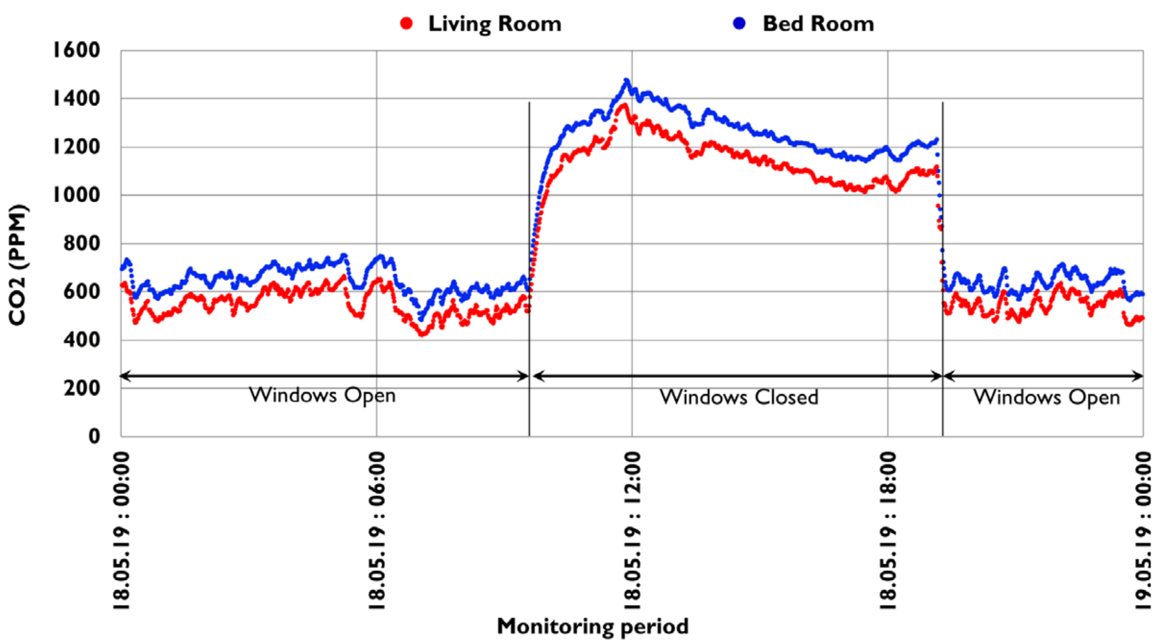

Figure 5: Graph showing monitored CO_2 concentration for a representative day inside the test flat (bedroom & living room)

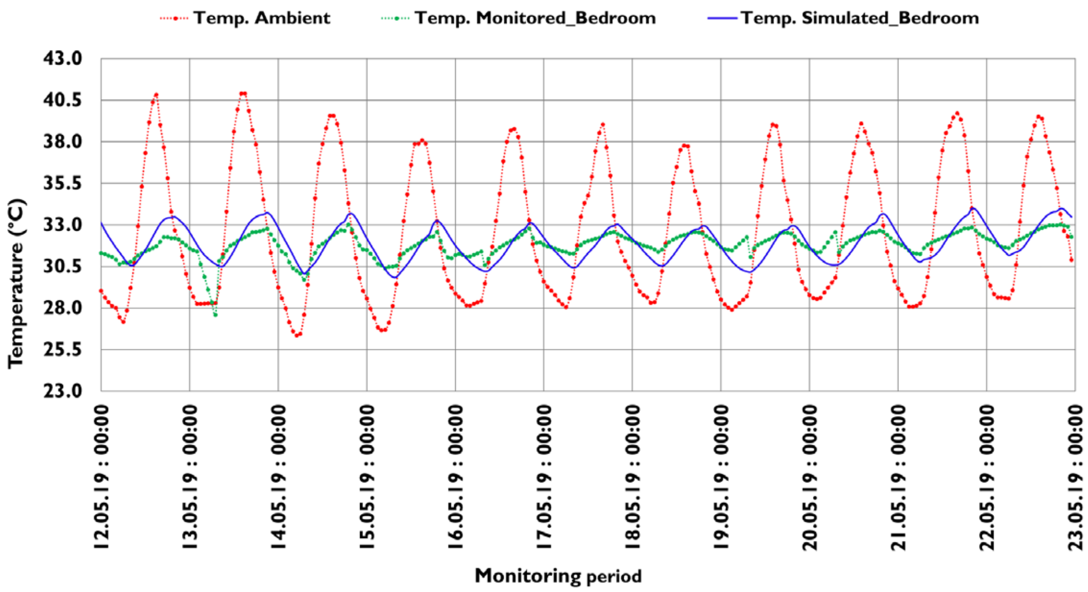

Figure 6: Graph showing comparison of measured and simulated bedroom inside temperature of the test flat.

CONCLUSIONS

The results of the monitoring show a quantifiable impact of building envelope (both construction material and openings for ventilation) on internal temperatures. It shows that with building envelope interventions it is possible to get maximum average temperature of 32°C in summer when the average maximum ambient temperature is 39°C, thus, increasing comfortable hours and reducing the need for air-conditioning.

The MBE and RMSE is calculated to be -0.09 and 0.7 respectively, which indicates a reasonably good match between the measured and simulated results.

NOMENCLATURE

DBT = Dry bulb temperature

NLPM = Normal litre per minute

RH = Relative humidity

ACH = Air change rate, h^{-1}

$\bar{Q}$ = Average air-flow rate or ventilation rate, m^3/h

Q_T = Instantaneous injection of CO_2 , m^3/h

C = Instantaneous CO_2 concentration, mol (CO_2)/ mol (air)

V = Volume of the space , m^3

t = Measurement period, h

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