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 m² 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 correspondence with the simulated results.

Keywords—Thermal comfort, Affordable housing, Passive design, Performance monitoring
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 Aerated 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 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* shows the parameters that were measured and the measuring equipment.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>INSTRUMENT</th>
<th>LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient DBT &amp; RH</td>
<td>Rotronic XD-33 Temp+Humi Sensor Transmitter with Weather Shield</td>
<td>Terrace; above the overhead water tank (OHT)</td>
</tr>
<tr>
<td>Roof-top wind speed</td>
<td>Wind Speed sensor (WIND-COMBO-1)</td>
<td>Terrace; above OHT</td>
</tr>
<tr>
<td>Roof-top wind direction</td>
<td>Wind Direction Sensor (Wind vane type potentiometer)</td>
<td>Terrace; above OHT</td>
</tr>
<tr>
<td>Indoor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedroom and living room DBT &amp; RH</td>
<td>Rotronic XD-33 Temp+Humi Sensor Transmitter</td>
<td>Centre of the room</td>
</tr>
<tr>
<td>Bedroom and Living room CO2 concentration</td>
<td>E-sense CO2 sensor</td>
<td>Centre of the room</td>
</tr>
</tbody>
</table>
Figure 1: Site plan showing the location of the test flat

Figure 2: Floor plan of the block with the test flat
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, CO₂ 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.
- 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 CO₂ for cost effectiveness, easy availability and for easy replicability of this test in other houses. A constant flow of CO₂ (3.6 NLPM) was injected into the space. In this case, the entire flat, excluding the WC and bath, was considered as one space.

CO₂ sensors placed in the bedroom and living room measured and logged the CO₂ concentration. Average ACH values were calculated for the day (windows closed) and night (windows open), using the following equation [2]:

\[
\frac{\bar{Q}}{\bar{V}} = \frac{Q}{V} - \frac{V}{\Delta t} \log_e \left( \frac{C_{\text{final}}}{C_{\text{initial}}} \right)
\]  

(1)

CO₂ 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 an 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/m²-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 °C. Thus compared to the diurnal variation of 11.5 °C in the ambient temperatures, the diurnal variation in indoor temperature was only 2.1 °C. 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 CO₂ was used to measure average air change rate (ACH) inside the flat using Equation-1.
  - From the measured CO₂ 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 23.4h⁻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 CO₂ concentration for a representative day inside the test flat (bedroom & living room)
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
\( \dot{Q} \) = Average air-flow rate or ventilation rate, m³/h
\( Q_r \) = Instantaneous injection of CO₂, m³/h
\( C \) = Instantaneous CO₂ concentration, mol (CO₂)/mol (air)
V = Volume of the space, m³
\( t \) = Measurement period, h

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REFERENCES