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Airflow and temperature modelling of sustainable buildings at the design stage can prevent unintended consequences of passive features

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Abstract

The integration of passive features during the design/construction of sustainable buildings requires thorough modelling at the design stage as some features may have unintended consequences resulting in occupant dissatisfaction, and resulting in the building using more energy to maintain comfort. This paper reports the outcome of an investigation into the thermal performance of a recently built 'sustainable science building' in a school located in South Australia. The building consists of a 115 m^2 atrium which is naturally ventilated by a solar chimney integrated into a high pitch roof with low level and celestial window openings at the outlet of the chimney.
The experiment was undertaken in January to monitor the airflow pattern and air temperatures at different location of the atrium. A mathematical model was used to predict the performance for comparison with experimental data.
At some hours, it was observed that flow reversal in the chimney led to unwanted hot air entering into the building thus increasing the building cooling load. The model was able to predict the flow reversal at those times. The use of such a model at the design stage can help develop an improved chimney design which avoids the undesired flow reversal and demonstrates the potential value of modelling of passive features before construction.

Keywords: Passive building features; passive building design; mathematical modelling; sustainable building

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1. Introduction

Integration of passive strategies into a building is fundamental in the design of sustainable buildings. Passive features are components that can be integrated as part of the building at the design stage to induce ventilation, cooling and heating with the aim of replacing/complementing mechanical systems. These elements may include solar chimneys, earth air tubes, wind towers, evaporative cooling, or Trombe-walls. The most challenging aspect at the initial design stage is to make sure that their intended purpose will be achieved. Most often the integration of these features into the design will be done by intuition and not supported by the use of simulation or decision support tools. As Attia et al[1] noted, among the main barriers of the decision making during the design of a sustainable building is the understanding of building physics and performance by architects. The same authors emphasized that in spite of the remarkable performance of some existing pre-decision evaluation tools, the tools are hardly used by architects who participate in the early design stage. Post occupancy evaluation of some sustainable buildings supported the evidence provided above.

Zion National park visitor centre (located in Utah, USA) incorporates passive features such as two cooling towers and clerestory windows [2] to provide natural ventilation and cooling. Two years post occupancy survey indicates that the cooling energy intensity was 77% less than a typical building in the region. Long et al. [2] recommended exhaust path consideration for improvement of the performance of cool towers. Lack of building integrated modelling on the design of passive evaporative cooling towers was found as the limiting factor faced at the initial design stage. Ford et al.[3] carried out performance evaluation of the combination of wind tower, evaporative cooling and thermal chimneys in a three storey mixed ventilated laboratory buildings in the Torrent Research Centre in Ahmedabad, India. The passive evaporative system uses micronisers for spraying water. Results from the first summer in operation indicate that internal temperatures are l0- 15°C below the peak external air temperature. In the top layer of the building however, air bypass was observed at the beginning of operation which could have been identified at the design stage if modelling was used.

An interactive learning centre at Charles Sturt University, Dubbo, Australia, includes four passive evaporative shower towers to provide cooling to 1600m^2 floor in combination of thermally massive walls and ceiling [4]. Its overall performance was found to be better than a conventional evaporative cooler while it is reported that the tower had performed poorly due to positive pressure developed in perimeter rooms which prevented the cool air from entering. This problem might have been prevented by modelling at the initial design stage.

This paper provides a case study on a recently built ‘Sustainable Science Centre’ in South Australia which was part of Building the Education Revolution program funded by the Australian government. Among the sustainable passive features in this building is a solar chimney integrated into the atrium of the building which acts as both internal shading device and promoting natural ventilation. The main aim of this study is to examine the actual operation characteristics of the solar chimney and to demonstrate how the use of modeling can lead to an improved design. In the previous publication [5], the details of the model used in this study has been presented.

1.1. Building description

The building consists of a 115 m^2 atrium which is naturally ventilated by passive airflow components and mechanical fans. The building is a light weight building mainly made of face brick and plasterboard. The atrium includes a manually operated low-level louver, a BMS (Building Management System) controlled high-level motorized louver, a built-in solar chimney which helps both to shade the transparent polycarbonate sheet roofing and to enhance natural ventilation, and finally, two BMS controlled variable speed axial fans. The solar chimney is constructed using polycarbonate sheets and six black painted sandwich panels filled with expanded Polystyrene (each with 2.7 m length, 1.7 m width and 75 mm thickness). The whole chimney is inclined at 35^o from the horizontal as shown in Figure 1. The polystyrene panels are operable and act as a roof shade. When they are closed, the whole channel acts as a solar chimney and they attenuate the light and radiation passing through the polycarbonate sheet. When they are open, they let daylight through the polycarbonate sheet roofing.

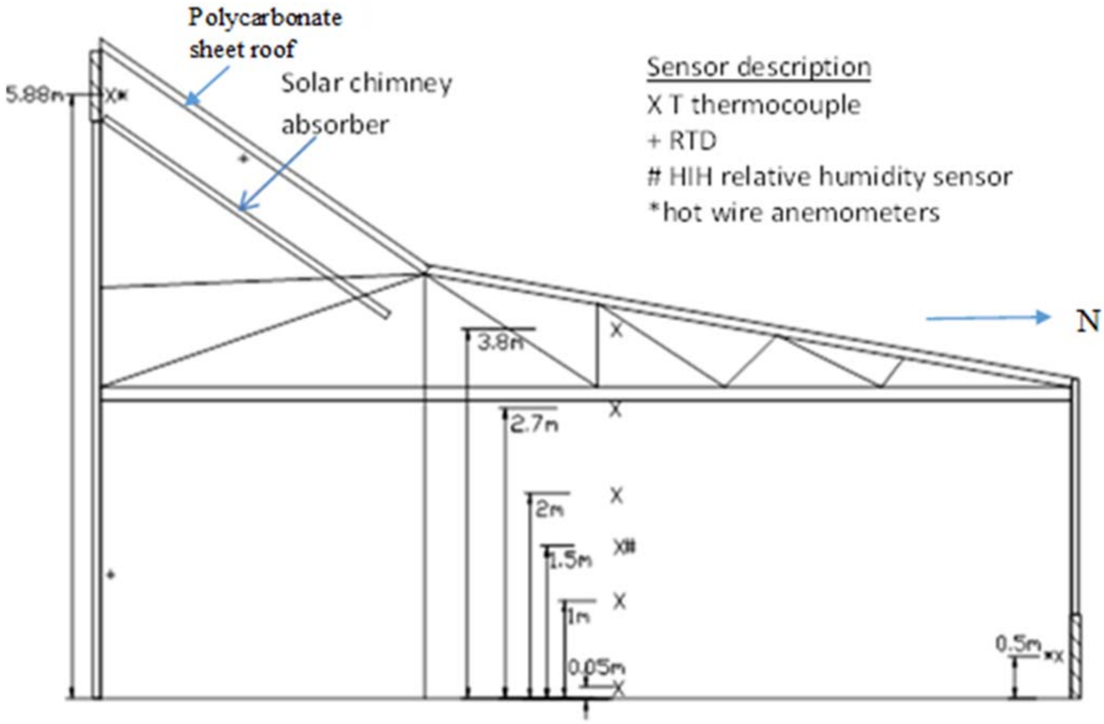

Fig. 1. Cross-section of the atrium showing the exact location of sensors

2. Test and model setup

2.1. Test setup

The test was conducted during the school break between 15th Dec 2011- 20th Jan 2012. During this period, the atrium was unoccupied. The data between 6th January- 20th January 2012 was available for model comparison. The building included a weather station, from which data was retrieved. The weather station provides the air temperature, wind speed and direction data, total radiation on a horizontal surface, and outside air relative humidity data. An i.button sensor was used to record the outside air temperature and humidity from the 6th January 2012. It was installed outside the atrium in the shaded area at the eave height.

Fig. 2 shows a photograph of the thermal and velocity sensors and the monitoring devices in the atrium. The exact location of the sensors is shown in Fig. 2. Six T-thermocouples were used along the mid-height of the atrium to account for thermal stratification and approximate the average room temperature. A HIH series relative humidity sensor was also installed at the mid-height of the atrium. An Omni-directional hotwire anemometer TSI 8475 with a T thermocouple was installed at the high louver opening. A TSI hotwire anemometer TSI 8460 with a T thermocouple was installed at the low louver opening. All the temperature sensors were calibrated with a reference RTD temperature sensor at three points in a precision room. The Omnidirectional TSI 8475 velocity transducer detects airflow in any direction. Its measuring range is between 0.05 m/s to 2.5 m/s. Its accuracy is 3%. TSI 8460 is a unidirectional velocity transducer with measurement range of 0-20 m/s. Its accuracy is 5% of the reading. Both anemometers were calibrated using a factory calibrated digital TSI anemometer.

Fig. 2. Photograph showing sensors and monitoring devices in the atrium

2.2. Model and input date description

A coupled Multizone ventilation and building thermal model has been developed by the authors [5] which has a capability of integrating all combinations of passive features such as a solar chimney, Trombe-wall, wind and buoyancy induced earth air tunnel. The mathematical descriptions of this model is presented in [5]. The input parameters used in the model are the site information including soil data, weather data (outside air temperature, wind speed and direction, direct and diffuse radiation, atmospheric pressure, dew point temperature) , atrium size and construction material properties, openings characteristics including the solar chimney, simulation time and control parameters such as daily and weekly scheduling . The major assumptions used are:

- The air temperature in the adjacent rooms equates to the arithmetic mean of the outside air temperature and the atrium air temperature.
- The solar chimney absorber was considered as a continuous plate neglecting the effect of gap between the EPS panels.
- The thermal mass effect of the timber trusses was ignored.
- Wind pressure coefficients for open terrain were used as the building is isolated in an open area
- The floor is uninsulated 100 mm polished concrete. An additional layer of 500 mm soil was assumed underneath and the boundary temperature at the bottom of the soil was assumed to be undisturbed soil temperature at that depth based on Juan and Baggs's equation [6].
- Effect of thermal stratification on airflow was not considered

3. Results and comparison to the model

3.1. Thermal stratification

A background study of thermal stratification was carried out with the data collected at the beginning of January. Fig. 3 shows the air temperatures at different heights in the morning and late afternoon for the sealed atrium (All louvers were closed) with a closed roof shade on the extreme hot day of 2nd Jan 2012. The temperature difference between the floor and the ceiling was 2 ^{0}C in the morning and reached to 6.5 ^{o}C at 3 pm. However in the region between 1 m-2.7 m from the floor, the air temperature was uniform within measurement reading error. The average atrium air temperature evaluated taking in to account all sensors is equivalent to measurements in the comfort region 1 m-2 m high from the floor. Minimal thermal stratification was also observed on more moderate temperature days.

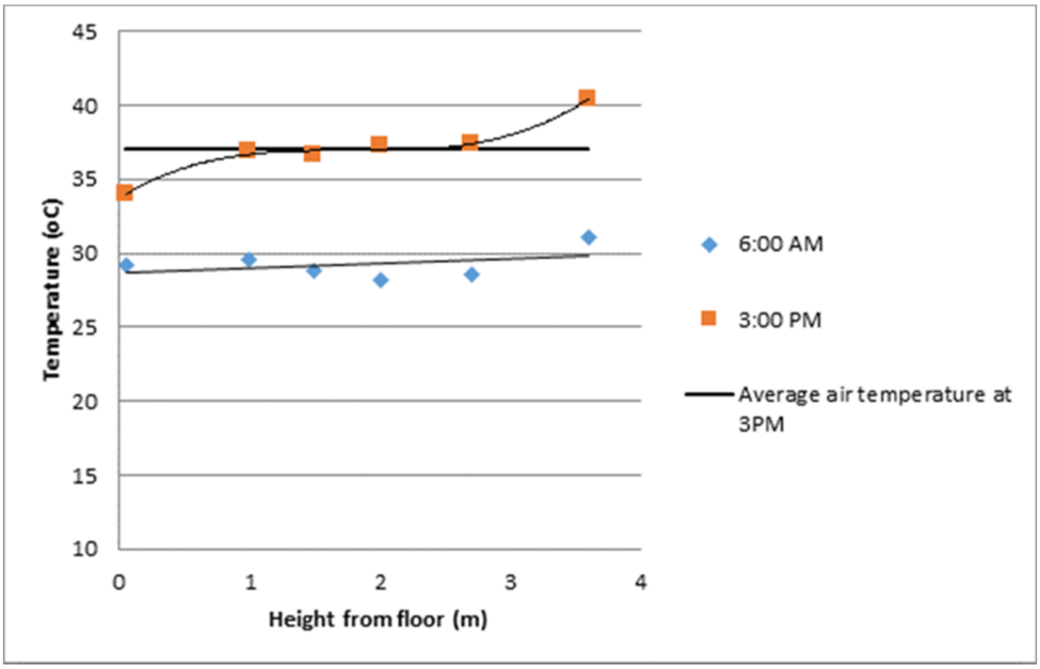

Fig. 3. Atrium air temperature with height; sealed building with roof shades closed, Jan 2, 2012; maximum outside temperature 43^{o}C

3.2. Comparison with model prediction

A comparison was carried out for three different testing periods. To allow for the transient effect due to model initialization, the simulation period after the first 24 hrs was analysed for comparison in all the three tests.

In the first test, the atrium was sealed with a closed roof shade. The test was carried out from 6-9 January. This data was used to calibrate the attenuation coefficient for the solar radiation passing through the polycarbonate sheet. This was achieved by matching the predicted atrium air temperature and the measured average air temperature in the atrium as shown in Figs. 4 and 5. The internal attenuation coefficient applied was 0.95 and this value consequently was applied in the other periods with similar configuration.

In the second test period, the roof shade was open and the atrium was exposed to direct solar radiation through the polycarbonate sheet roof. The measurement was carried out from 9th Jan-13th Jan 2012. Both louvers were open between 8 am-12pm and the lower louver remained open until 4 pm. The opening times were controlled by the building management systems and the authors were not able to get access to the BMS admin. The airflow components in this configuration are therefore low-level and high-level large vertical openings. In this scenario, both stack ventilation (between 8 am-12pm) and displacement ventilation (between 12pm and 4 pm) were observed. Figs. 6 and 7 show comparisons between the measured and predicted average atrium air temperature and airflow through the louvers respectively. Fig. 6 shows good correlation with the measured temperature data. Some variation between the measured and the predicted air temperatures was observed for few hours. For example, on 11th Jan at 10 am, the predicted air temperature was 2.3^{o}C higher than the measure value. At this time, the predicted average air velocity at low-level louver was 0.08 m/s while the measured air speed was 0.68m/s (Fig. 7). Consequently more cool air entered into the room than predicted. The difference may be attributed to the nature of the wind fluctuation and the uncertainty of the pressure coefficients used in the model.

The predicted atrium air temperature for the case if all the louvers were closed for the test period is also shown in Fig. 6. The comparison shows the cooling effect of the natural ventilation. For example, at 10 am on 11th Jan, the air temperature without ventilation would be 4^{o}C higher than that of the naturally ventilated atrium.

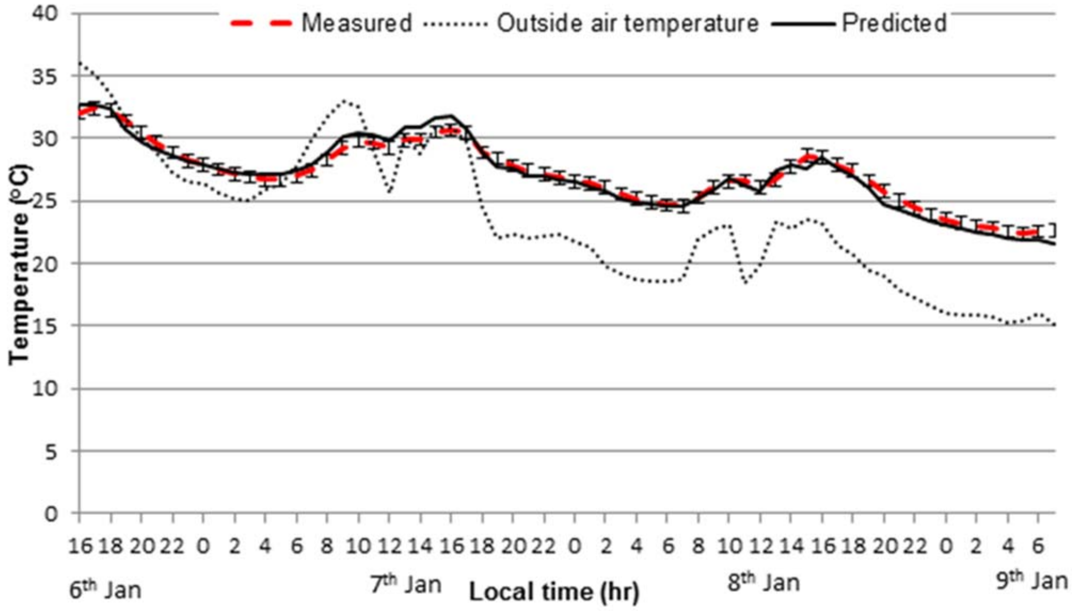

Fig. 4. Comparison of average air temperatures in a sealed atrium and roof shades closed (Jan 6-9 2012)

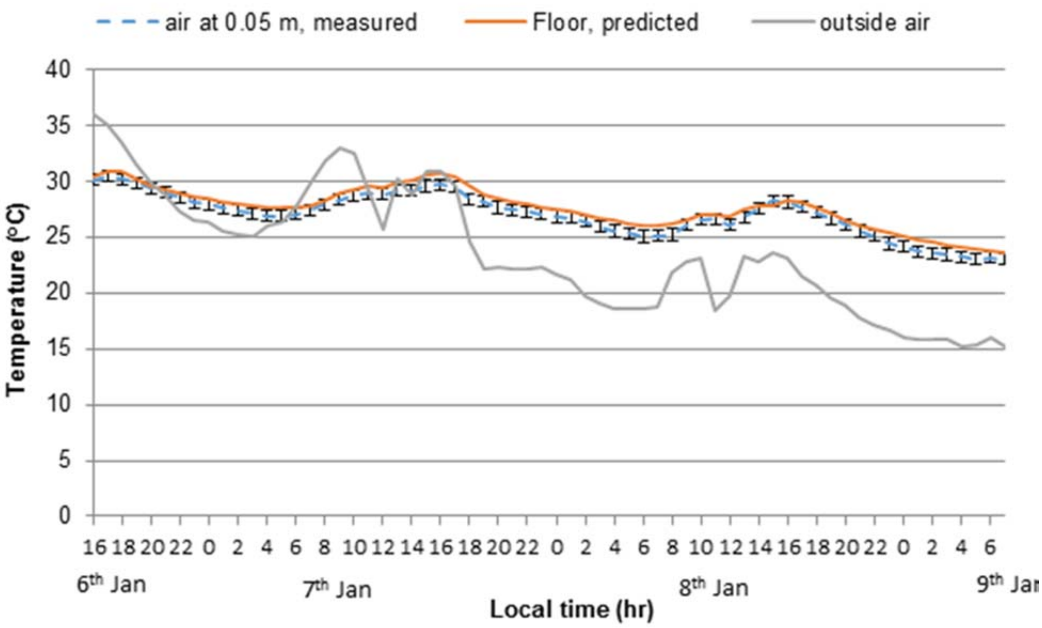

Fig. 5. Comparison of predicted floor temperature with measured air temperature near the floor in a sealed atrium with closed roof shade (Jan 6-9 2012)

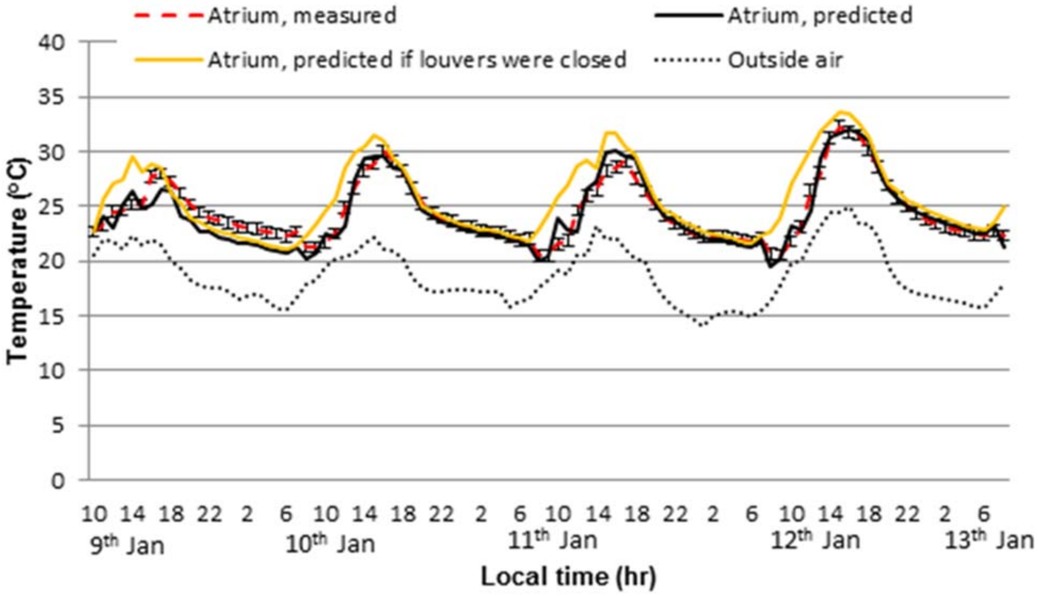

Fig. 6. Comparison of average atrium air temperature with the roof shades open (Jan 9-Jan 13, 2012)

In the third test carried out between Jan 14-20, 2012, the roof shade was closed and louvers were open between 8am-12pm except during the weekend. The airflow components in this configuration are vertical low-level large openings and an inclined solar chimney. Fig. 8 presents the measured and predicted atrium air temperatures between 14th Jan and 20th Jan. The model compares well with the measured data for the entire time when the louvers were closed. However, the variation was significant on the 16th and 17th Jan, when the louvers were open. For example, the difference between the predicted and measured air temperature reached 3.4 ^{o}C at 12 pm on the 16th Jan. At this time, the predicted average air velocity at the chimney exit was 0.6 m/s while the measured air speed was only 0.22 m/s as shown in Figure 9. The ventilation input parameters such as the wind pressure coefficient may contribute to the flow discrepancy, as measured wind pressure coefficient values were not used in the model. For comparison, a simulation was also run assuming closed louvers for the whole period, and it was observed that the measured air temperature value was between the two predicted values during 8-12 pm (Fig. 8). On the 19th Jan, the measured air temperature was higher by 1.5 ^{o}C at 12 pm and it was observed that the predicted average air velocity at the chimney exit was 0.17 m/s while the measured air speed was 0.4 m/s. This comparison shows that the air temperature prediction was consistent when airflow predictions were close to measured values. Consequently, the variation between the predicted and measured airflow rates can be attributed to the uncertainty associated with the wind pressure coefficients and wind speeds and directions at particular hours.

As the hotwire anemometers cannot detect the direction of the airflow, the model predictions were used to evaluate if there is any flow reversal in the solar chimney. The model was able to show flow reversal in the solar chimney in some hours, which resulted in heated air, entering the atrium from the chimney. Fig. 10 shows the predicted airflow rate at the solar chimney and the corresponding wind direction on the 19th Jan. Air entered into the atrium through the chimney at 9-10 am as the southern wind opposed the buoyancy induced by the solar chimney. Fig. 11 shows the exit air temperature from the solar chimney for opening hours of 8am-12pm on the same date. For the two hours when flow reversal occurred, the outside air entering the atrium was heated up in the solar chimney by 1.4 ^{o}C at 9 am and 2.9 ^{o}C at 10 am. This scenario demonstrates an important factor, which the model can predict. The use of this model at the design stage can help to come up with an improved chimney design which avoids the undesired flow reversal.

To summarise, this work shows that building models can predict performance accurately if used properly and at least will give qualitative support for decision at initial design stage whether the innovative passive features will provide their intended functions. The solar chimney used in the 'Sustainable Science Centre' looks great at a glance as it provides three functions such as internal shading, enhancing natural ventilation and when it is not required it will be moved to the vertical wall to allow daylight through the skylights. The case study on this building however has shown that the internal solar chimney with clerestory window as its outlet is not a great idea. One of the main problem is the exhaust path consideration: during windy days, if the clerestory window is in the windward direction, flow reversal via the solar chimney will likely to happen which consequently let heated air by the chimney into the atrium. Using the chimney absorber as an internal shade will also increase the heat gain into the building via convective heat transfer as it basically acts as an inclined ‘Trombe wall’ even though this evidence is not included as part of this study.

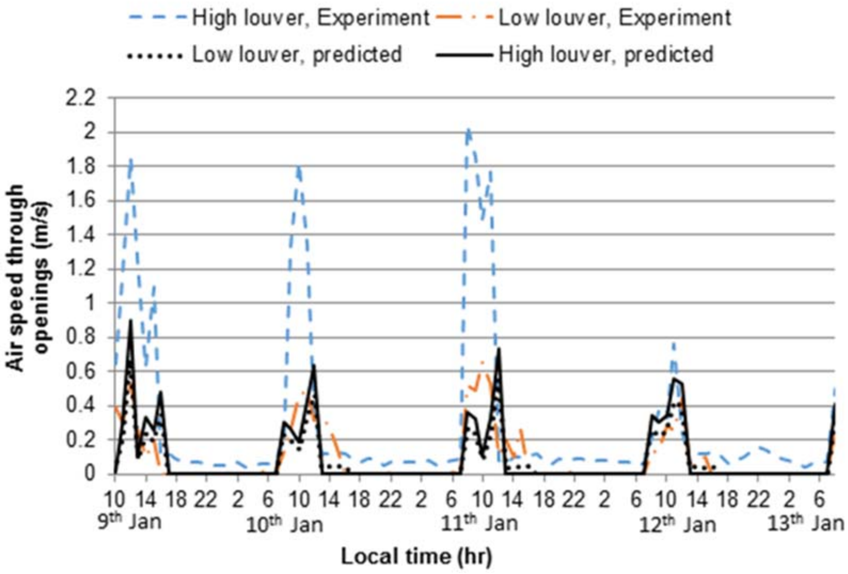

Fig. 7. Airflow rates comparisons across the low and high level louvers: predicted and measured, roof shade open (Jan 9 - Jan 13 2012)

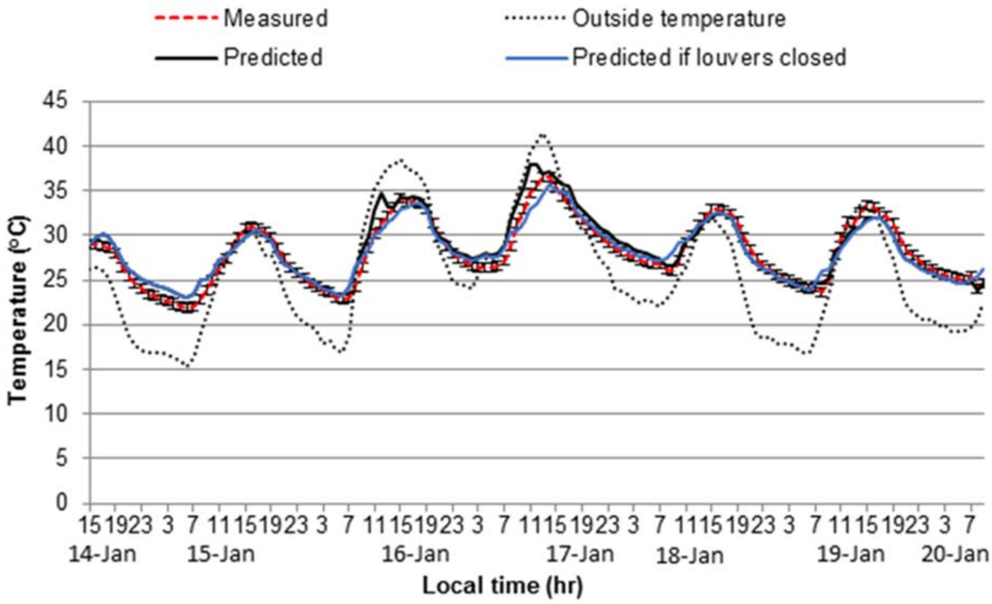

Fig. 8. Comparison of predicted and measured atrium air temperature (roof shade closed; Jan 14-Jan 20, 2012)

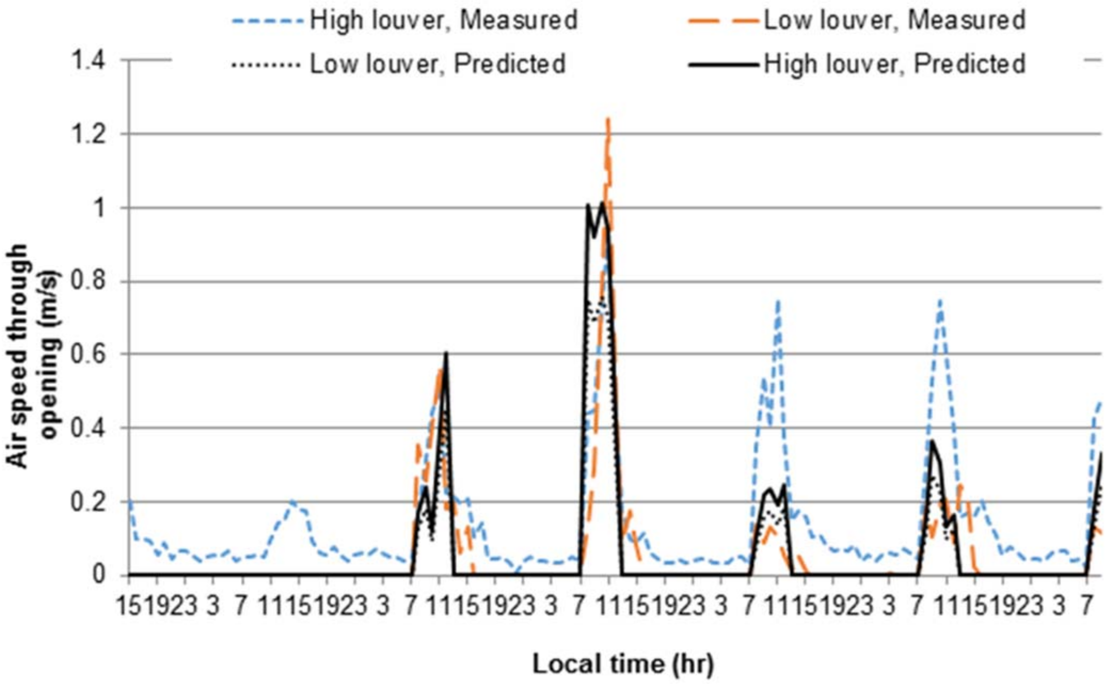

Fig. 9. Comparison of predicted and measured airflow rates through openings in the atrium (roof shade closed; Jan 14-Jan 20, 2012)

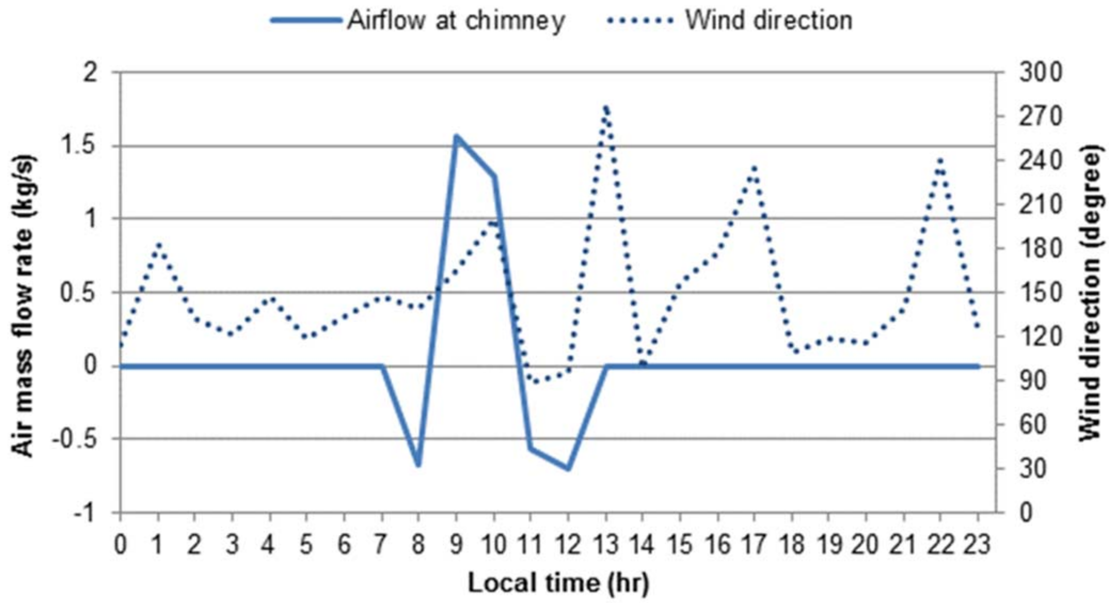

Fig.10. Predicted airflow rate at the solar chimney and the corresponding wind direction on 19th Jan 2012 (Wind direction: 0^o refers to North, +Ve indicates air flow into the atrium)

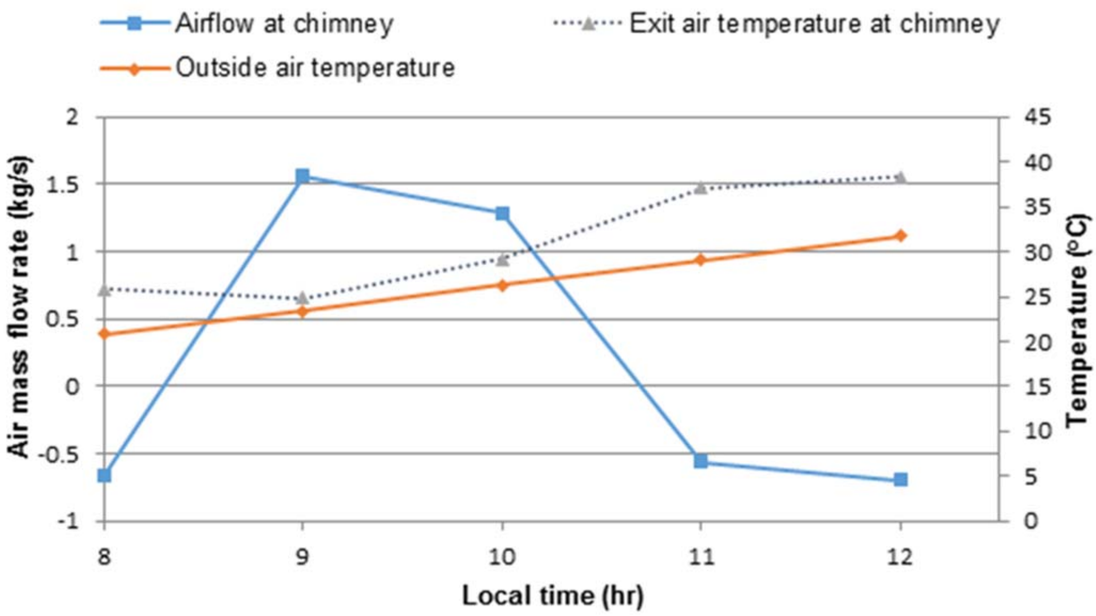

Fig.11. Predicted flow reversal and exit air temperature from the solar chimney on 19th Jan 2012

4. Conclusion

The case study provided in this paper demonstrates that the innovative passive features may not perform as intended which will have a negative consequence on occupant perception of sustainable building features. Overall, the outcome shows the importance of modeling at the initial design stage to integrate passive features in buildings and to determine the appropriate sizes and configuration of passive elements.

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