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Passive Cooling Performance of a Solar Chimney and Vertical Landscape Applications in Indonesian Terraced House

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Grahical abstract

Abstract

Natural ventilation has been promoted as passive indoor cooling technique in hot humid tropical region. However for a single sided window in a typical deep plan terrace house, the effect of natural ventilation is questionable. It is worst when coupled with the fact that available wind in Malang is almost static and unreliable. This paper presents alternative passive technologies integrated to existing terrace house in the city of Malang to achieve indoor cooling assisted by solar chimney and green vertical landscape. A field measurement was conducted using Onset Hobo Data Logger for a specific duration. The solar chimney is installed inside the house harnessing the thermal stack effect of hot air buoyancy that naturally forced the cyclic air movement letting hot air out and bringing in cooler air. The vertical green landscape installed just outside the front window provide shade and filter the incoming air providing cooler and cleaner air. The result showed that the average indoor temperature is within the acceptable comfort range for the whole day. This is considered a significant achievement where the use of solar chimney and green vertical landscape can improve indoor thermal condition thus provide alternative for natural cooling, reduce energy use and healthy environment.

Keywords: Passive cooling performance; solar chimney; vertical landscape; terraced house

1.0 INTRODUCTION

This paper explores the performance of two passive cooling systems; the first is using solar chimney and whilts the second employing vertical landscape. The solar chimney is to force the wind acceleration while the vertical landscape provides sun protection. Both systems are designed to provide cooling load control while improving thermal comfort. In addressing these issues, passive cooling system design solutions must account the constraints of latitude, location and solar orientation. The hypothesis is that passive cooling systems or design strategies can provide solutions to many of these challenges in building design today. While the focus is on passive cooling system design, the scope of this paper is limited to solar chimney and vertical landscape of the selected dwelling unit in the city of Malang, Indonesia.

1.1 Previous Studies

The tropical humid climate, especially in Indonesia is characterized by high temperatures and high relative air humidity. Dehumidification is one of the ways of solving the problem of high humidity allowing sufficient airflow through the buildings thus increasing comfort condition. Therefore, provision for air movement is an important considerations in building design. According to Prianto and Depecker[1], air temperature and humidity when combined in the enthalpy have a strong impact on perceived air quality and determines the required ventilation. The environmental parameters to determine thermal comfort are air temperature (Ta), mean radiant temperature (MRT), water vapour pressure (Pa) or relative humidity (RH), relative air velocity (Vt), and personal parameters such as clothing or thermal resistance and activity or metabolic rate (M)[2].

Passive cooling is one of the important options in providing thermal comfort in buildings[3], thus reducing the need for mechanical cooling. The building design should maximize the natural ventilation and minimize the fraction of sun energy absorption[4]. Providing adequate natural ventilation would reduce the cooling load of a building in tropical areas. Two major goals in natural ventilation include provision of sufficient fresh air and satisfactory temperature. At temperatures below 34°C, which is the average temperature in many hot and humid conditions, air movement might be one of the most useful and least expensive methods to provide a comfortable indoor climate. Further, the movement of air across human skin creates a cooling sensation. This is due to heat leaving the skin through convection and by the operation of perspiration[5].

A solar chimney is a natural ventilation device, which utilizes solar radiation energy to build up stack pressure, thereby driving air flow through the chimney channel. The use of solar chimneys as ventilation devices can be found in some historical buildings, such as the so-called "Scirocco rooms" in Italy, which dated back to at least the 16th century, where the solar chimneys were used in conjunction with underground corridors and water features to provide ventilation and cooling[6]. In the past decade, solar chimneys have attracted much attention in various investigations including by Barrozi[7] who modeled a solar chimney-based ventilation system for buildings. The roof of a building performed as a solar chimney to generate air flow and provide cooling for the living room. Experimental tests were carried out on a 1:12 small-scale model of the prototype. Bouchair[8] showed that for his 1.95 m high and variable width chimney which was electrically heated, the optimum ratio of chimney width/height is 1/10 for maximum air flow rate. However, when the chimney was too big, reverse circulation occurred with a down-ward flow. Bansal[3] developed a steady state condition where he developed a mathematical model for solar chimney system consisting of solar air heater connected to a conventional solar chimney. The estimated effect of the solar chimney was shown to be substantial in promoting natural ventilation for low wind speeds.

Alfonso[9] compared the behaviour of a solar chimney with a conventional one. They presented a thermal model and transient simulation of a solar chimney by applying a finite difference model to the chimney brick wall assuming unsteady state one-dimensional heat transfer in the direction of the brick wall and not along the flow. Khedari[10] studied the feasibility of using roof and wall to induce ventilation. They showed a significant potential of passive solar ventilation of houses. The Roof Solar Collector could be formed below a heated roof to draw air from the inner spaces of a building. Hirunlabh[11] studied the performance of a metallic solar wall for natural ventilation of building in Thailand. Theoretical and experimental studies on the natural ventilation of buildings were also carried out by him for four different combinations of height and air gap. Satwiko[12] found a Solar Wind Generated Roof Ventilation System for low cost dwellings located in high building density urban area. The roof prototype can generate evenly distributed vertical cross ventilation within the occupant's zone. Miyazi[13] investigated the performance of a solar chimney, which is integrated into a south façade of one-story building, as well as the effect on the heating and cooling loads of the building by using a CFD simulation and an analytical model. Nugroho[14] assesed the passive cooling performance of a solar chimney using field measurement and showed that it canreduce the air temperature.

Vertical landscape is a general technique that has been used in many countries around the world. It has proved to be effective in hot climate regions. Currently, its functions are widely utilized and researched, especially for passive cooling and pollution reduction[15]. The use of the green vertical landscape or vertical green climbers can be effectively used to provide alternative passive cooling. The vertical landscape can provide shade to protect external wall from direct solar radiation. It can also shade the window area and filter pollution. At the same time vertical landscape indirectly reduce heat and thus give sense of natural cooling. The used of vertical green landscape not only mitigate micro climate of its immediate surroundings, ease on indoor comfort but also reduce the need for air conditioning, thus lowering energy used in building. It can improve other urban environmental issues such as instant flood by slowing down rain and surface water discharge and filter noise. The greater impact is that it can increase the proportion of green areas that is lost horizontally[16] and providing new scenery and horticultural therapy[17].

1.2 The Selected Case Study Houses and Local Context

The selected case study houses are located in Griya Saxofone housing estate, Malang, the second largest town in East Java, Indonesia. The terraced house are parallel to the main road which is 10 m width and considered within an urban area. The two selected houses are middle units in a typical row or block. The typical size of the lot is about 8 m in width and 10m in depth (Figure 1). Figure 2 shows the full scale application of solar chimney and vertical landscape in the experimental house.

Figure 1 A single storey terraced house in Malang, used for field measurements

The climate of Indonesia (latitude 6º North and 11º South and 95º and 141ºEast longitudes) is generally characterized by high relative humidity and air temperature. Meteorological data for Malang city in the year 2012 illustrate that the mean monthly air temperature was consistent and varies slightly by only 3,1ºC, from 21,6ºC in July to 24,7ºC in November. The average daily air temperature is about 23.3ºC throughout the year. Its relative humidity ranges from 69 to 85 %.

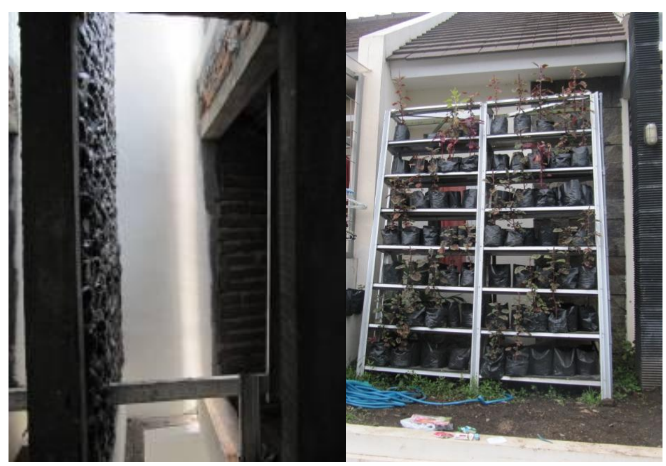

Figure 2 The solar chimney and vertical landscape as passive cooling system

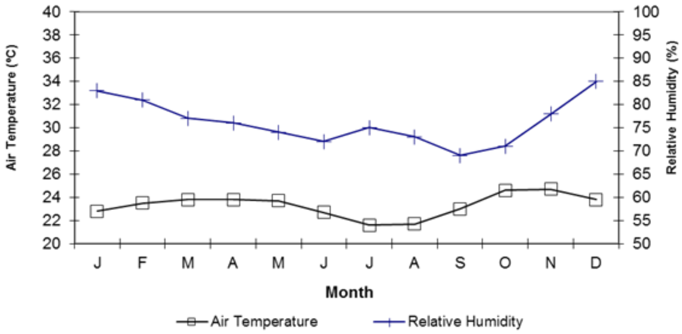

Figure 3 Seasonal pattern of airtemperature and relative humidity (Data obtained 575m above sea level at the Malang Meteorological Station, 2012)

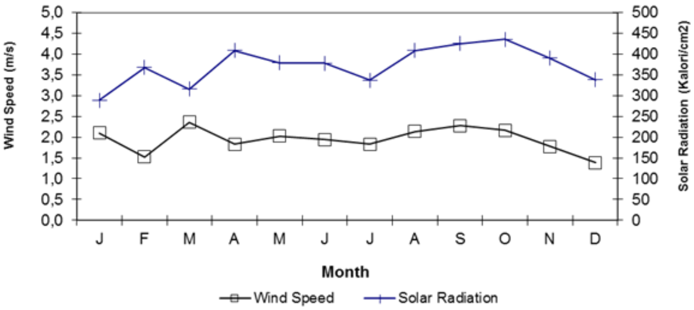

Figure 4 Seasonal pattern of solar radiation and wind speed (Data obtained 575m above sea level at Malang Meteorological Station, 2012)

The average solar radiation is 372 kalori/cm2 each month, and is of high radiation during October and of low radiation during January. Figure 4 and Figure 3 show a combination of high solar radiation with increasing air temperature from October to November, which results in extremely over-heated period. During this period the mean wind speed also indicated higher values.

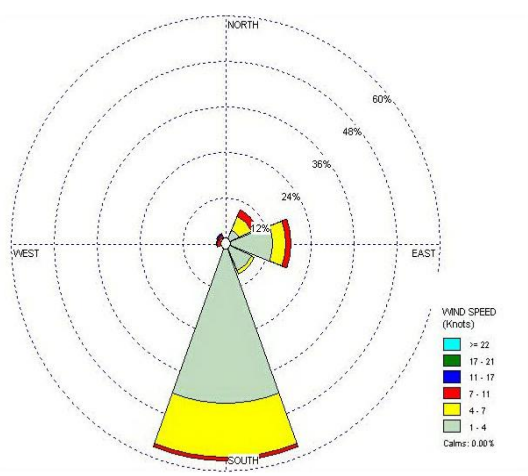

Figure 5 Wind rose in Malang (Data obtained 575m above sea level at Malang Meteorological Station, 2012)

Figure 5 indicates the wind roses during the year 2012 at weather stations in Karangploso, Malang, Indonesia. As shown in Figure 5, the mean wind velocities in the south wind indicate higher values than those in the other wind directions. Therefore, the influences of the south wind can be seen throughout the year. The effects of the the west wind are not remarkable compared to east wind.The percentage values for the calm conditions indicate 0% as shown in Figure 5. The calm condition indicates that the mean wind velocity was equal or less than 0.3 m/s.The mean wind velocities between 0,5 m/s–2 m/s are relatively stronger than those of the wind velocity in south wind direction.

2.0 RESEARCH METHODOLOGY

A field survey to determine the environmental parameters of a typical single storey terraced house in Griya Saxofone housing estate, Malang was conducted from November 2012 to December 2012. The two typical houses (similar in design) comprised two different rooms and was kept empty without furniture to reduce the thermal exchange between objects. The windows of the living and master bedroom face towards the east while the windows of the kitchen and two other bedrooms face toward the west. Except for the living room, all other rooms received natural ventilation through single side openings. The windows have single sash, which were retrofitted by the occupants. The window sashes (1 m height, 1.5 m width, and 1m above the floor) are fixed in the kitchen and bedrooms while the living room had a sliding window (2 m height, 1m width, 0.2 m above the floor).

As in a typical Indonesian dwelling, the windows are usually kept open during the day and closed at night for security reason. During the measurement, all doors remained closed and all windows of the house remained open (Figure 6). The walls and roofs are not insulated for heat transmission. The building structure consists of 150 mm thick brick walls (including cement and lime plaster). The thickness of the outside and inside walls is 20 cm and 15 cm respectively. The total U value for the walls was about 0.5 W/m2 K. The instrumentation consisted of sensors with a data logger system. The sensors were setup to monitor outdoor and indoor climatic conditions. Figure 6 shows the positions of the instrument installation within and outside the house with solar chimney and vertical landscape.

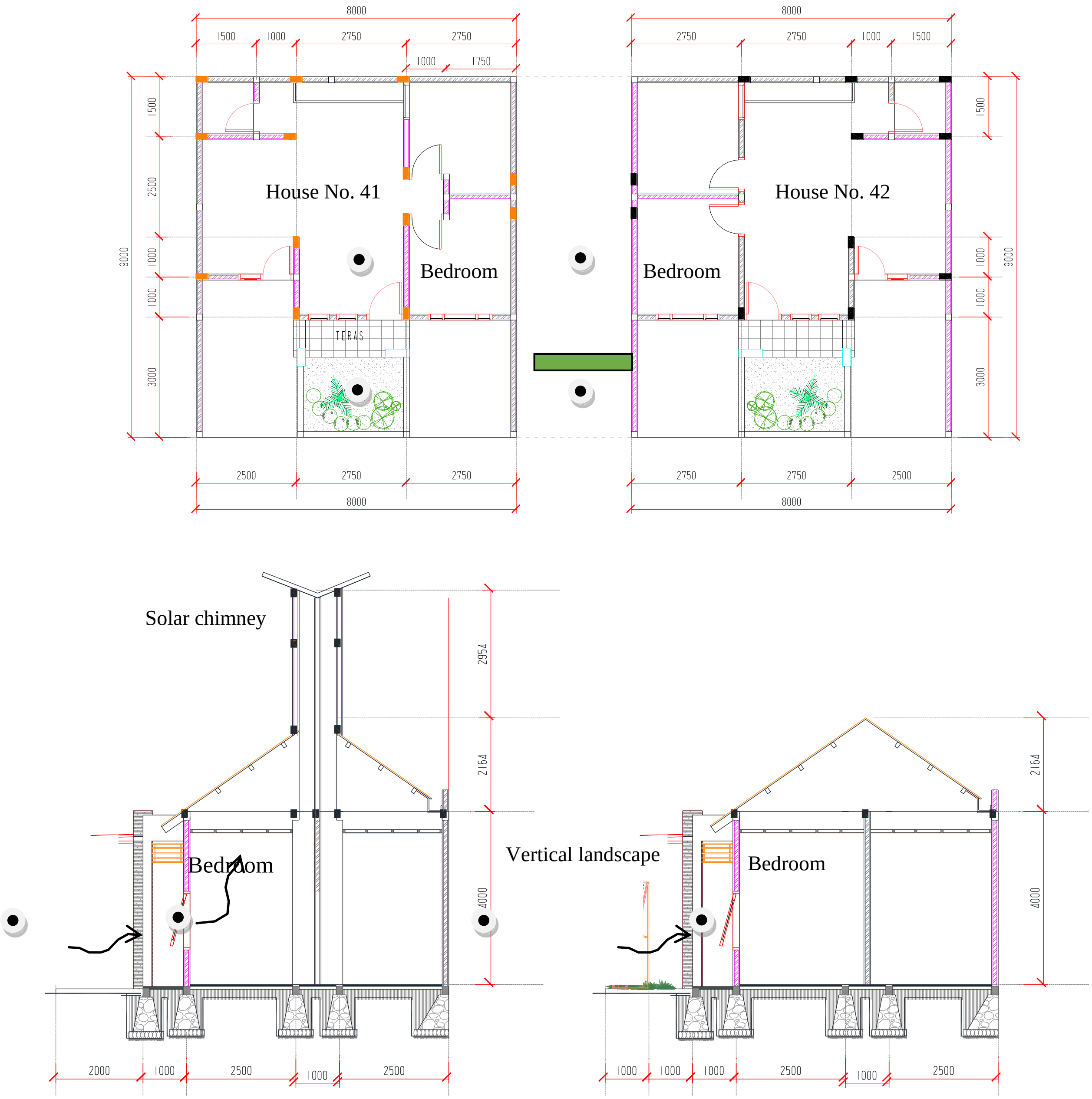

Figure 6 The positions of onset hobo data logger in single storey terraced houses (●); the top is plan and the bottom is west section

Air temperature and the relative humidity were selected as the main variables to determine the thermal environment as suggested by Prianto[1] and Nugroho[5]. The field measurements were obtained using the Onset Hobo Data Logger as mentioned earlier the meteorological data for the year 2012 in Malang suggested that the mean monthly air temperature remains constant[18]. The analytical method of evaluating the comfort zone for hot humid climate have been studied by several researchers, using the "Neutrality Temperature"[5,12,14,19] and also used in this study. This is the temperature at which the respondents in the various studies experienced neither warm or cool, which is a state of "neutral" or "comfortable". It is the midpoint of the comfort zone, an average value for many experimental subjects. There are four different factors that can combine together to produce different neutral temperature for an individual, these are: thermal environment, activity level, clothing or thermal resistance and physiological state of the individual[2]. For adults the neutrality temperature range from 17°C to 30°C and the range of neutrality temperatures is effectively 13 degree[19]. But it is necessary to conclude that acclimatization also had affect on the temperature required for thermal neutrality. The comfort temperature or neutrality temperature can be predicted from the linear equation for naturally ventilated building as cited in Nugroho[5]: $Tn = 17.8 + 0.31 \times Tamt$, where, Tn = neutral temperature with+/- 2°K range and $Tamt$ = annual mean air temperature of the month. To get comparative comfort zone, the above equations were used and the annual mean air temperature of the month was worked out from the climatic data for Indonesia. This will give a general picture of the range of comfort zone for Indonesia. According to Auliciems and Szokolay[19] with the range of the comfort zone is taken as 5°C, thermal comfort temperatures extends approximately about 2.5°C above and below the neutral temperature. While Humphrey's equation[19] gives a good approximation of a single comfort temperature in free running buildings, the thermal comfort zone defined using solely this technique does not accommodate the influences of thermal comfort in hot and humid climates.

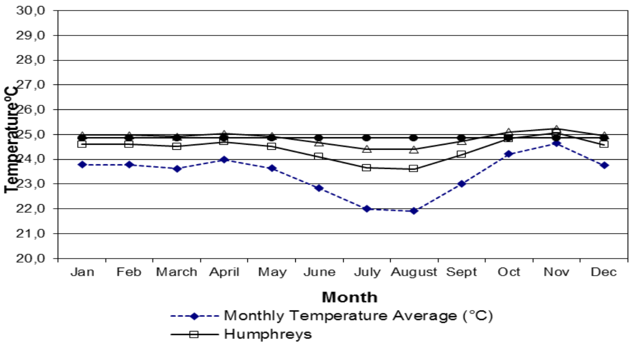

Figure 7 The Neutral temperature on the Malang monthly data

Daily climatic patterns in the tropics required climate conscious building design strategies to achieve thermal comfort. Outdoor temperature for monthly data is plotted in Figure 7. According to Figure 7 the outdoor air temperature reached 24.6°C in November. The lowest temperature was reported as 21.9°C in August and the average temperature is about 23.4°C. According to Szokolay comfort formula[6], the neutral temperature needed to maintain 24.9ºC. With the width of the comfort zone taken to be 5ºC [6], thermal comfort temperatures extends approximately about 2.5ºC above and below the neutral temperature. Taking the neutral temperature of 24.9ºC in free running building as an illustration, the upper limit of the comfort zone would then be 27.4ºC. This neutral temperature is for conditions without air movement.

3.0 RESULT AND DISCUSSION

The result discussed the critical need for modification in all aspects of ventilated design. The challenge for modification is also further complicated if we are addressing a complex building system that is dynamic and responsive to the changing need of the occupants, building owner and societal needs. However, the discussions will focus on the challenges of providing cooling through natural ventilation modification in two different levels namely using solar chimney and vertical landscape.

3.1 The Impact of Solar Chimney

The relationship between indoor and outdoor temperatures of a terraced house based on hourly data is shown in Figure 8. The change of indoor temperature is small compared with the outdoor temperature. It is clear that the indoor temperature of the terraced houses is lower than that of the outdoors except in the night. Further, in the daytime, the outside air temperature could be as high as 31.6ºC assisted by maximum solar radiation at 12:00 h. During the morning and noon hours, the air temperature inside the building is almost the same as the outdoor air temperature (at 07.00 h and 17.00 h). However, between 19.00 h and 06.00 h the inside air temperature is 0.1°C–2.2°C hotter than the outdoor air temperature. The indoor thermal environment during the investigation demonstrated a similar profile in the hourly pattern of temperature and relative humidity. The changes of outside air temperature was intensed, while the inside air temperature remained stable compared to the outside. The inside air temperature was below 26.6°C when the outside maximum air temperature was about 31.6°C. Further, as Szokolay comfort formula[6] indicates, if the average indoor temperature is 25.5°C between 8.00 h and 19.00 h, the particular room is considered within the comfort zone.

Hence, the field measurements indicated that the case study with Solar Chimney is within the comfort zone (24.2) for 24 hours. Figure 8 indicated that the outdoor relative humidity ratio is lower than the indoor relative humidity level during the daytime. After the inside air is heated at noon to the level of the outdoor air temperature, its relative humidity remains essentially the same for a few hours. The range is slightly more for conditions with no or slow air movement and decreases with higher air speeds. The relative humidity inside the bedroom fluctuated between 55% and 72%, and the outdoor between 41% and 84%. The relative humidity of the indoor was a little constant than the outdoor. The reason may be explained by the fact that the solar chimney received intense solar heat in the day, and since there is inadequate air velocity, the solar heat may accumulate.

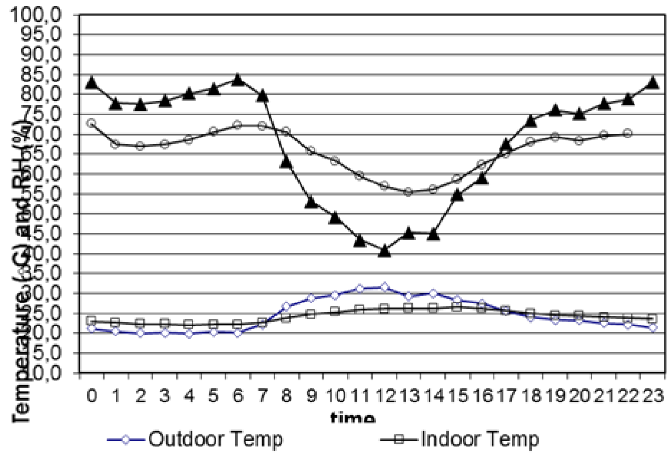

Figure 8 Comparison of outdoor and indoor air temperature and relative humidity at 0.9 m height from floor level with the use of Solar Chimney

In this study, the potential of solar chimney ventilated design was assessed in tropical climate. Figure 8 shows the daytime hourly air temperatures of the terraced house with a solar chimney. When the solar chimney was installed, the daytime mean air temperature was 25.5˚C. The average air temperature in the terraced house was considered within the neutral temperature in Malang (between 22.4°C-27.4°C). Thus, the target neutral temperature can always be achieved.

3.2 The Impact of Vertical Landscape

Landscape are important considerations in urban housing design to reduce and absorb solar radiation. The measured temperature is shown in Figure 9. Clearly, the diurnal air temperature of the outdoor is higher than the indoor temperature in hotter season. The temperature difference is above 2.5°C with a maximum value of 5.8°C. Furthermore, due to different kinds of shading and ventilation arrangement, there are temperature differences among different rooms at the same floor and the maximum difference can be above 2°C. In the night time, the temperature of outdoor is about 0.5°C lower than indoor temperature. Figure 9 showed that the outdoor relative humidity is lower than the indoor relative humidity level during the daytime (08.00 h-16.00 h). The lower limit of relative humidity is around 57%. The relative humidity inside the house fluctuated between 80% and 92%, and the outdoor between 57% and 98%. The relative humidity of indoor was a little constant than outdoor.

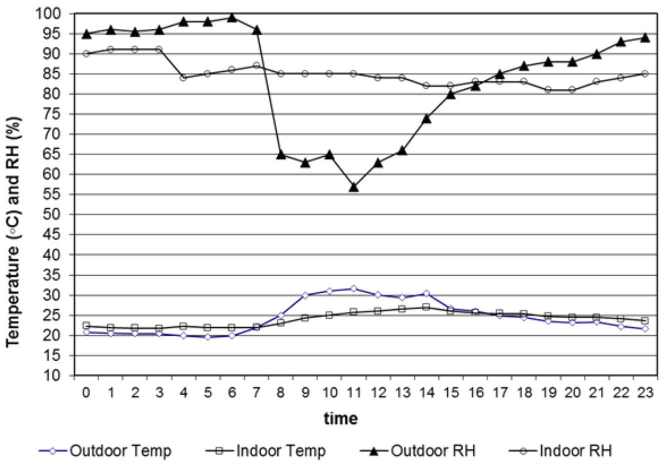

Figure 9 Comparison of internal-external temperature and relative humidity at 0.9 m height from floor level with the use of vertical landscape

■4.0 CONCLUSION

The study has emphasized that installation of solar chimney and vertical landscape can have great affect on the indoor thermal condition in a hot humid climate like Malang, Indonesia. The field measurement was used to investigate the thermal environmental condition within selected rooms. The result of thermal environment for typical house show that it is unable to provide thermal comfort, especially in the master bedroom. With modifications being applied, the results of the field measurement showed that the use of solar chimney and vertical landscape indicated the average indoor temperature is within the comfort zone of neutral temperature for 24 hours. Further, the use of solar chimney is considered more succesfull than vertical landscape when employed in the terraced house. There are two reasons to support this finding. Firstly, the thermal strategy of the design has considered the roof solar ventilation and solar stack ventilation including the materials use and structure of the building envelope. Secondly, the passive cooling system is an auxiliary facility for a better indoor thermal environment in the day and in the night. The design strategy is to restrain the ventilation during the daytime and to boost it at night with the use of solar chimney. Simple architectural modifications and a few changes in the usage patterns may result in a reduction of the indoor temperature of maximum of 5.5°C and minimum temperature of 1.4 °C respectively. Clearly, the research has shown that it is possible and worthwhile to apply this novel idea to the modern terraced house building design for passive indoor cooling and energy saving.

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