

A new configuration of roof skylight combined with solar chimney

DOI:10.36909/jer.16259

Anon Anan-archa* Preeda Chantawong** Joseph Khedari***

*Ph.D. Student, Energy Engineering Technology Program, Department of Power Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand.

**Associate Professor, Energy Engineering Technology Program, Department of Power Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand.

***Professor, Division of Industrial Technology, Faculty of Science and Technology, Bangkokthonburi University, Bangkok 10170, Thailand.

**Corresponding Author: cpreeda@yahoo.com, preedac@kmutnb.ac.th

ABSTRACT

This paper reports experimental performance of a new modular configuration of roof integrating skylight and solar chimney intended to reduce heat gain admission, induce ventilation and ensure sufficient indoor illuminance. This integrated Skylight Solar Chimney (SSC) configuration is composed of three layers: a 1mm thick clear acrylic layer on the outside, a set of 1 mm thick aluminum slats distanced each other at the middle and a layer with a combination of clear acrylic and aluminum slats at the inner side. To assess SSC performances, two small rooms of 2.52 m³ volume were built using concrete blocks for walls and corrugated cement panels for the south facing roof sloped at 30 degrees. The roof of the first house, which served as a reference, integrated a transparent corrugated panel whereas the other house integrated our SSC. The dimensions of the SSC are 0.50 m x 1.50 m x 0.15 m (W x L x H). A 0.025 m² outlet opening was located at the top lateral side whereas two inlet openings of similar surface area were installed on the bottom lower layer (one inside the room and another outside). Field test results showed that in all scenarios considered the indoor temperature of room with SSC was 1 to 4 °C lower that of the reference room and varied

following ambient conditions. When both inside and outside inlet openings were used, the highest temperature difference was observed. The measured heat flux through the roof of reference house was much more important than all SSC scenarios, a 50% difference was observed when both SSC inlets were open. This clearly demonstrated SSC efficiency to reduce heat gain. The air change (ACH) induced varied between 2 to 29. SCC indoor illuminance was about 50% lower than that of the reference house.

Keywords: Skylight Solar Chimney; Thermal performance; Natural ventilation; Daylighting.

INTRODUCTION

In hot and tropical countries, the important part of heat gain admission is due to the roof as it is continuously facing the sun radiation. Modern houses and buildings built using concrete and glazed windows with poor ventilation experience excessive indoor temperature. Also, as direct sunlight increases heat accumulation inside the indoor space, typical residences often avoid the use of natural daylighting by extending the roof design to cover the walls whereas office building use curtains limiting natural daylight and adopt the use of lamps that consume electricity. Low-e windows are expensive solutions and few architects adopt them in the country. To deal with the problem of heat accumulation, residents use mechanical air conditioning to lower the indoor temperature that increases electricity consumption.

Worldwide concern about climate change, environment protection and energy consumption in residences and buildings has motivated researchers, engineers, architects and professionals to conduct extensive efforts to develop efficient systems, materials, equipment and design (Suliman et al., 2021, Shari et al., 2021). In the last three decades, considerable amount of research work focused on the use of solar chimney, stack effect and skylight to play multiple roles including heat gain reduction, ventilation and daylighting. The literature is very rich and a complete review of these topics is out the scope of this paper. Based on conventional solar chimney design with an air gap and two spaced layers, several innovative design configurations both for roof and wall were introduced and tested worldwide (Khedari et al., 1997, Lee et al., 2009, Khedari et al., 2000, Chantawong et al., 2006, Drori et al., 2005 &

Khanal et al., 2014) with a significant contribution of Thai researchers (Khedari et al., 1997, Hirunlabh et al., 2001, Khedari et al., 2000. & Chantawong et al., 2006, Ananacha et al., 2013, Thateenaranon et al., 2017. & Ratanachotinun et al., 2016). Interesting review of solar chimney application and building ventilation were reported in (Zhai et al., 2011) and (Harris et al., 2007) respectively. Authors also considered the use of heat trapped in the roof cavity to induce ventilation (Vincenzo et al., 2018, Gagliano et al., 2012, Biwole et al., 2008, & Amornleetrakul et al., 2014). To improve ventilation, multi solar chimneys configurations were developed (Hassanein et al., 2012, Wei et al., 2011, Mohsen et al., 2019 & Jing et al., 2015). Wetted roof (Chungloo et al., 2007) and the use of phase change material (PCM) (Kosny et al., 2012) were also among attempts for performance improvement. The glazed wall solar chimney reported in (Chantawong et al., 2006) was aimed to increase ventilation and allow sufficient daylight inside the building. The Building Scientific Research Center (BSRC) multipurpose bioclimatic roof reported in (Waewsak et al., 2003) not only improved ventilation when compared to simple roof chimney configuration but allowed reasonable indoor daylighting. A wall configuration with external fin shading was investigated in (Ananacha et al., 2013). Full-scale investigation of the BSRC bio climatic house that included several building envelope configurations, i.e., Roof Solar Collector (RSC), Modified Trombe Wall (MTW), Bio-climatic Roof (BCR) and Glazed Solar Chimney Wall (GSCW) and economical assessment of wall and roof construction were published in (Thateenaranon et al., 2017) and (Ratanachotinun et al., 2016) respectively. However, despite all improvement made, wide application of solar chimney-based ventilation and skylight in Thailand is still very limited due to the relatively high back period about 7.39 years (Thateenaranon et al., 2017) and excessive daylight intensity and glare of skylight when applied. In addition, most research concentrated on the development of new envelope configurations and didn't address existing residences and buildings sufficiently where there is a high potential for application especially low-cost houses.

This paper developed a modular configuration of new roof envelope that functions like a solar chimney and a skylight simultaneously. It can be pre-assembled to be installed on new roof or to replace part of existing roof.

THE SKYLIGHT SOLAR CHIMNEY

The design concept of our new roof configuration integrating skylight and solar chimney, referred to as Skylight Solar Chimney (SSC), is illustrated in Figure 1. SSC is composed of three layers: a transparent layer on the outside, a set of opaque slats distanced each other at the middle and a layer with a combination of transparent and opaque slats at the inner side. The transparent layer is to allow incident radiation to enter the SSC and reduce short wave radiation emitted to sky. This is to increase air gap temperature and induce high ventilation rate. The set of distanced opaque slats at the middle is aimed to absorb part of the incident radiation whereas the voids will allow the remaining part of the incident radiation to reach to the third layer. The transparent slats of the third layer will admit the direct incident radiation and the reflected one inside the SSC into the indoor space whereas the opaque slats are aimed to protect this.

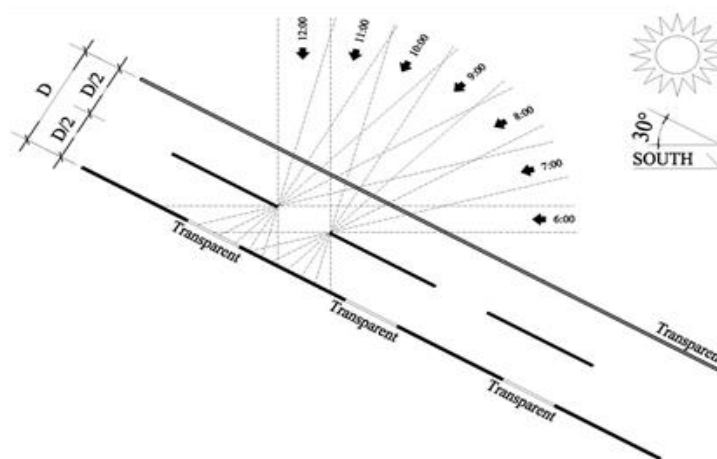


Figure 1. Design concept of the Skylight Solar Chimney.

Also, as suggested in (Waewsak et al., 2003), SSC shall allow some direct sun radiation penetrating into the indoor space only in early hours in the morning. This is to offer warmer space in early hours in the morning as ambient temperature is relatively low varying between

10 to 20 °C especially in northern part of Thailand during winter (Khedari et al., 2001). During 10:00 to 16:00, no direct sun radiation should be allowed to avoid excessive indoor space heating and glare.

EXPERIMENTAL METHODOLOGY

In this paper, we consider an air gap of SSC equal to 150 mm. This distance is widely recommended for solar chimney configuration in various published papers (Khedari et al., 1997. & Hirunlabh et al., 2001, Khedari et al., 2000. & Chantawong et al., 2006, Ananacha et al., 2013, Thateenaranon et al., 2017. & Ratanachotinun et al., 2016). Based on the design conditions discussed in the section above, we can determine appropriate dimensions of the various slats by simple geometrical calculation for a south facing roof slopped at 30°. Also, and for simplicity of manufacturing, we adopt the width of the opaque slats to be twice than that of the voids (middle layer) and transparent slats (bottom layer). The dimensions of a modular unit of the SSC are 0.50 m wide, 1.50 m length and 0.15 m thickness. The materials used are 1 mm clear acrylic and 1 mm thick aluminium plate. Figure 2a shows section of the SSC with dimensions of all materials used calculated proportional to the SSC length (L) and gap (D). Plans and dimensions of the middle and bottom layers of the SSC are given in Figure 2b. It should be pointed out the total available surface area for incident radiation admission through the middle and room side layers of SSC is practically equal to that of the local roof which is 0.428 m² (0.23 m² for the voids of the middle layer and 0.23 m² for the transparent slats of the inner layer).

To assess SSC performances, two small rooms of 2.52 m³ volume were built using concrete blocks for walls and corrugated cement panels for the south facing roof slopped at 30 degrees. The first house integrated a unit of our SSC whereas the second, which served as a reference and referred to as typical local roof, integrated a clear corrugated acrylic panel. Figure (3) shows elevation and dimensions of the two experimental houses and figure (4) shows photographs of the typical and SSC houses built.

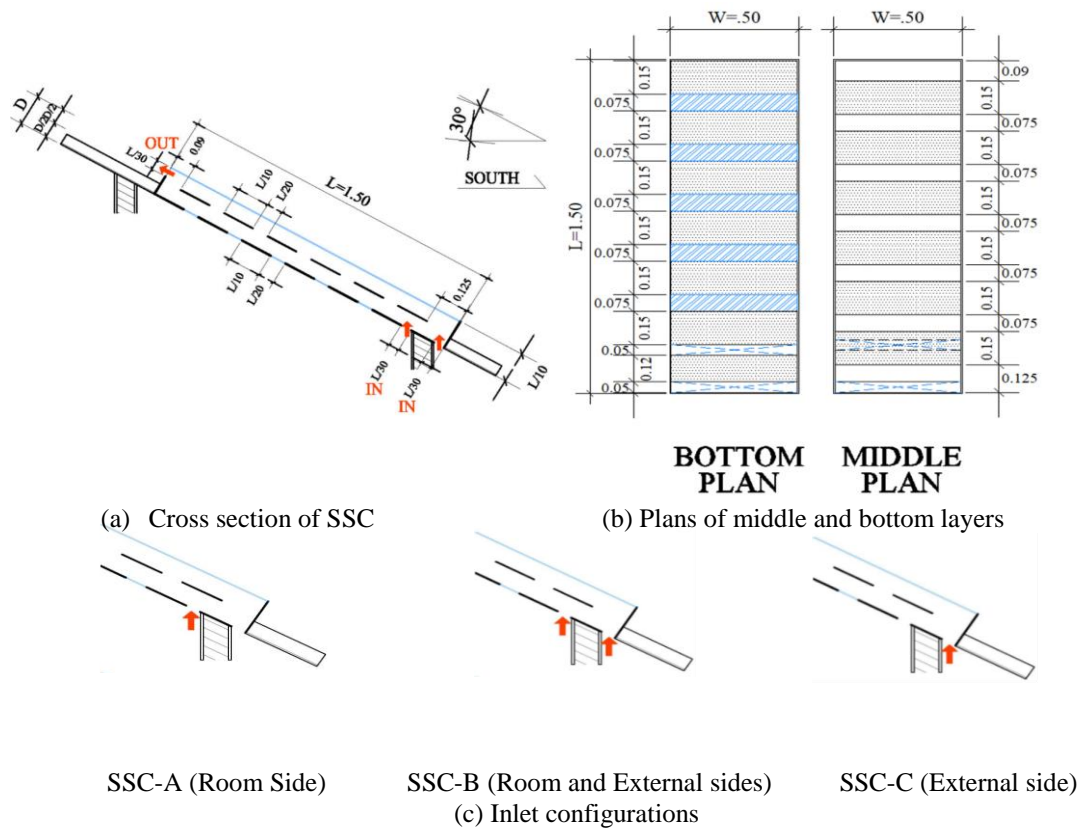


Figure 2. (a) SSC cross section (b) middle and bottom layers (c) inlet configurations.

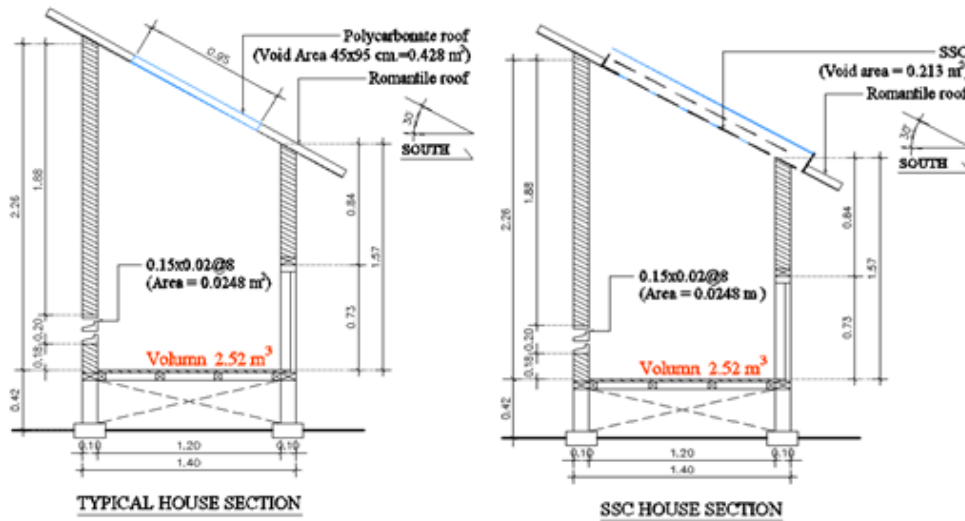


Figure 3. Section and dimensions of typical and SSC house models.

At the top side of SSC, a 0.025 m² outlet opening was located whereas two inlet openings of similar surface area were installed on the bottom lower layer (one inside the room and another one outside, Fig.2c). Three scenarios of SSC configurations with open room inlet, outside inlet and both room and outside inlets open were considered. Table 1 shows the thermal and physical properties of various materials used. Field tests were conducted in Samut Sakhon province, southwest of Bangkok (Nadee Subdistrict, Samut Sakhon, latitude 13.606342, longitude 100.3143494) for different days and different inlet configurations considered.

Table (1). Thermal and Physical properties of various materials used. (https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html, <https://www.chi.co.th/article/article-861/>, https://www.engineeringtoolbox.com/density-solids-d_1265.html, Hanan et al., 2016)

Material	Thermal Conductivity (W.m ⁻¹ .K ⁻¹)	Specific Heat (kJ.kg ⁻¹ .K ⁻¹)	Density (kg/m ³)
Aluminium	222	0.896	2739
Clear acrylic	0.2	1.43	1.19
Concrete Block	0.303	0.84	960
Corrugated Cement Panel	0.993	790	2400

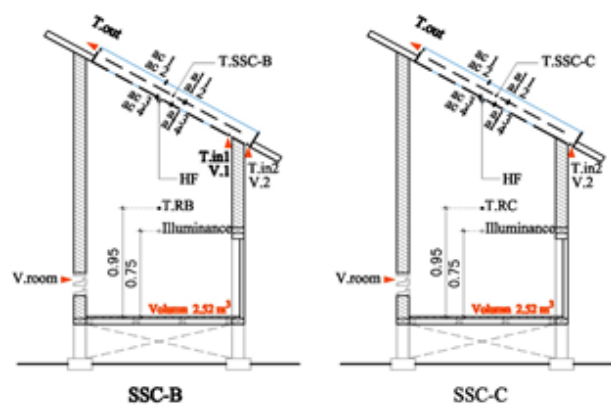
Figure 5 shows the location of the sensors used for measurement of various parameters of the two houses for the different inlet configurations considered. The intensity of incident solar radiation was measured using Si-Pyranometer EKO Instruments (ML-01), irradiance range 0 - 2000 W/m², accuracy ±3.07%). Temperatures at several positions were measured using thermocouple type K (range -270 to 1260°C accuracy ± 0.4%). Air velocity was measured at different positions using Benetech (GM8903) hot wire anemometer used in the range 0-30 m/s (accuracy 0.001m/s). A heat flow sensor (Hioki Z2015, range accuracy ± 2 %) was used to measure heat flux through the roof. Indoor illuminance was measured at 750 mm from the floor at the centre of rooms using SNDWAY (SW-582) lux meter with wide measurement range of 0-200,000 lux. Two data acquisition loggers (LR 8432 and 8402) were used to record data continuously from 6 a.m. to 6 p.m.

RESULTS AND DISCUSSION

Field tests were conducted during several days and various ambient conditions. In this paper, measured data are reported for three different days and three inlet configurations considered. Although ambient conditions were different, subjective analysis and reasonable comparison could be made.



Figure 4. Photographs of the typical house (top) and Skylight Solar Chimney House (bottom).



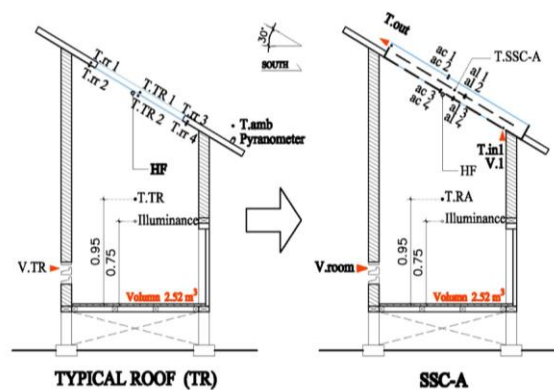


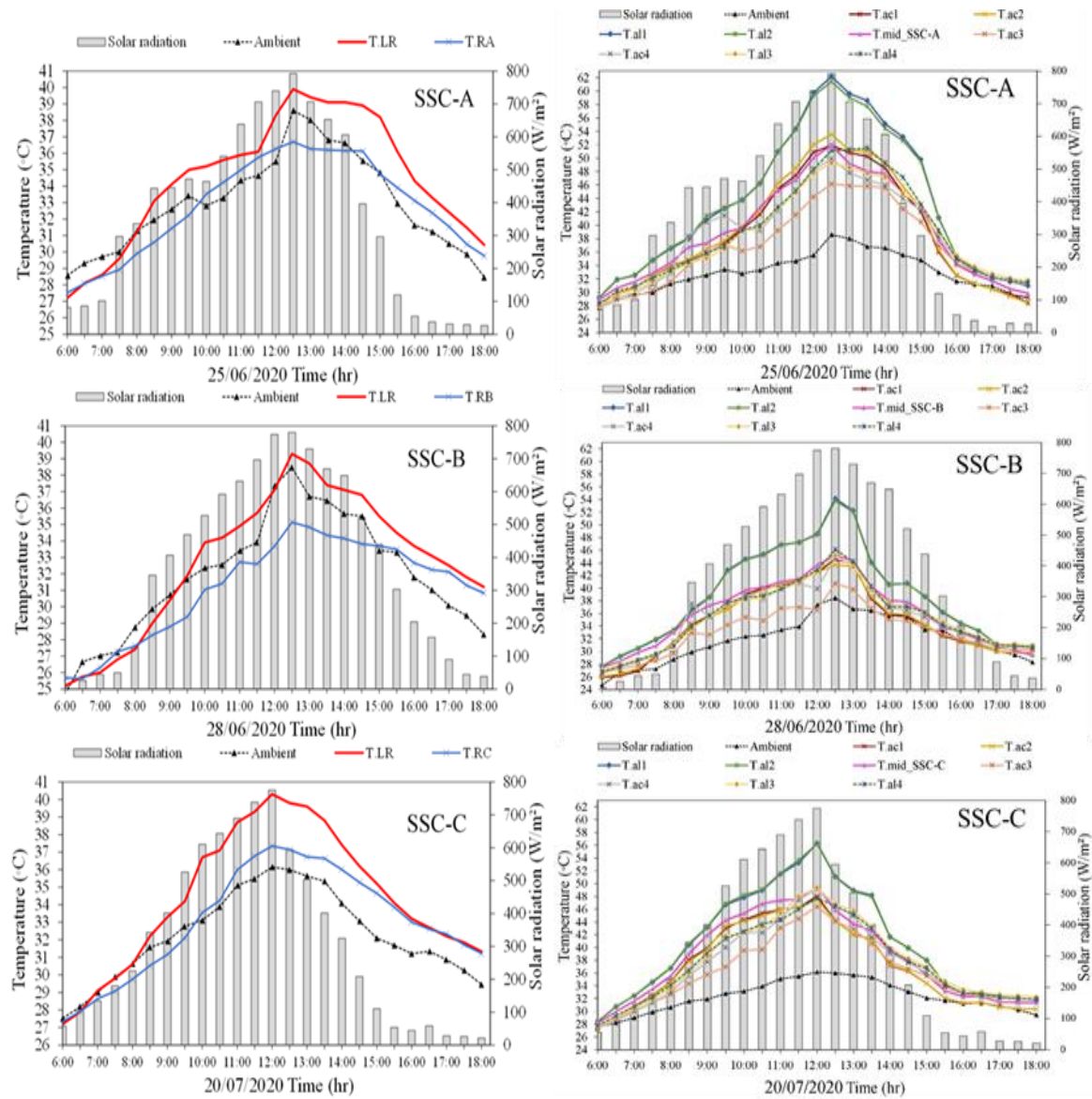
Figure 5. Locations of the sensors used for measurement of the different cases considered.

Figure 6.left shows the hourly variations of indoor temperature of the typical and SSC houses, ambient temperature and solar radiation for the three inlet configurations considered. It is observed that the variations of indoor temperature of the two houses followed well the incident solar radiation. The higher is the incident solar radiation, the higher the indoor temperature. The indoor Room Temperature of all SSC configurations (T.RA, T.RB, T.RC) is practically near or lower than ambient temperature whereas that of the Local house (T.LR) is often higher; the maximum recorded was about 4°C higher than ambient temperature. The SSC room temperature was 1 to 4°C lower than that of the typical house for all three inlets configuration considered. The highest temperature difference (4°C) between the typical room and the SSC room is observed around 12:00-13:00 when both room and soffit inlets are used (SSC-B). This can be explained due to highest ventilation induced by SSC. In fact, opening soffit inlet enhances the stack ventilation induced and lead to better removal of indoor air and lowering heat accumulation inside the SSC house. During daytime the average indoor air temperature reduction varied between 2 – 3 °C compared to that of ambient air temperature that is extremely satisfying. When external inlet is only used (SSC-C), it can be observed that in the morning and despite the fact that there is no ventilation induced by SSC (room opening is closed), the indoor temperature of SSC house is lower than that of the local house. This

observation clearly demonstrate that our SSC can act as a good insulation material reducing heat gain admission. However, in the afternoon, the temperature difference between the typical room and the SSC room decreased significantly as more heat is accumulated and no indoor ventilation is induced. In all cases considered, the highest is the incident solar radiation, the more important the temperature difference between the two rooms. When compared to published literature on several configurations of roof solar chimney (Khedari et al., 2000, Waewsak et al., 2003. & Thateenaranon et al., 2017) our results agreed well and that validate our SSC configuration as a good new alternative roof design.

The measured temperatures at the middle of SSC of the different materials used of the three different layers, Figure.6.right, varied well following ambient conditions; maximum temperatures were recorded around noon. With open room and soffit inlets, (SSC-B), temperatures were lower when compared to the two other inlets configurations due to the high ventilation rate induced as discussed earlier. Due to their small thickness, no significant difference between the upper and lower surface temperatures of solid materials is observed.

Figure 7 shows that the air gap temperature varied well following ambient conditions. It increased gradually from the inlet along the SSC length. The maximum air gap temperature is observed at the middle of SSC where most incident heat is trapped.



Tac.1, Tac.2, Tac.Tac.4 top and lower surface of external and internal acrylic layers
 Tal.1, Tal.2, Tal3, Tal.4 Top and lower surface of aluminium slat at the middle and lower layers
 T.SSC-A, T.SSC-B, T.SSC-C air temperature at the middle layer

Figure 6. Hourly variations of (left) indoor temperature of typical house (T.LR) and SSC house (T.RA, T.RB, T.RC) and (right) temperatures of SSC materials at the middle and ambient temperature and solar radiation for the three inlet configurations considered.

At SSC exit, temperature is decreased due to contact with ambient air. Such variations are typical to solar chimney and agreed well with published data (Khedari et al., 2000. Waewsak et al., 2003). With open room and soffit inlets, (SSC-B) and under sufficient amount of incident solar radiation throughout the whole day, there is noticeable temperature difference between the middle and outlet of SSC when compared to the two other inlets configurations. This also an indication of the high flow rate induced ventilation by SSC that ensures gradual

increase of temperature. The temperature at inlet of the external side is higher than that of the inlet at room side due to sensor position.

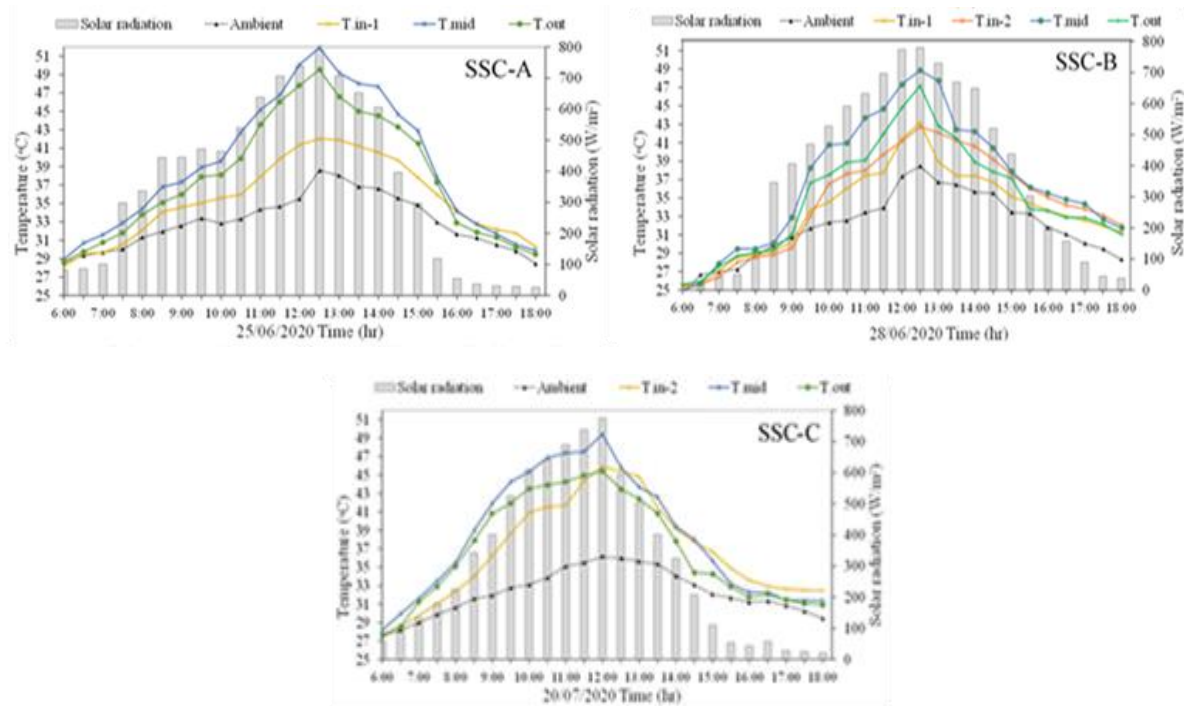


Figure 7. Hourly variations of measured temperatures of air at inlet (T.in-1 at room side, T.in-2 at external side), middle (T.mid) and outlet (T.out) of the SSC, ambient and solar radiation for the three inlet configurations considered.

The measured heat fluxes through the roof, Fig.8.left, increased in the morning and decreased in the afternoon following the incident solar radiation. Due to SSC design configuration and the ventilation induced that reduce surface temperatures of different materials, the measured heat flux transmitted through SSC is significantly lower than that of the local roof in all inlet configurations considered. The highest difference of about 50% is observed with room and external side inlets configuration (SSC-B). These results clearly demonstrate the efficiency of SSC acting as a good insulator. The measured indoor illuminance at 75cm from floor, Fig.8.right, of the SSC house with the three inlet configurations considered is about half that observed in the typical house and that clearly demonstrate SSC ability to reduce excessive indoor illuminance. An improved configuration SSC ensuring daylighting near the recommended standard of 300 lux deserve investigation.

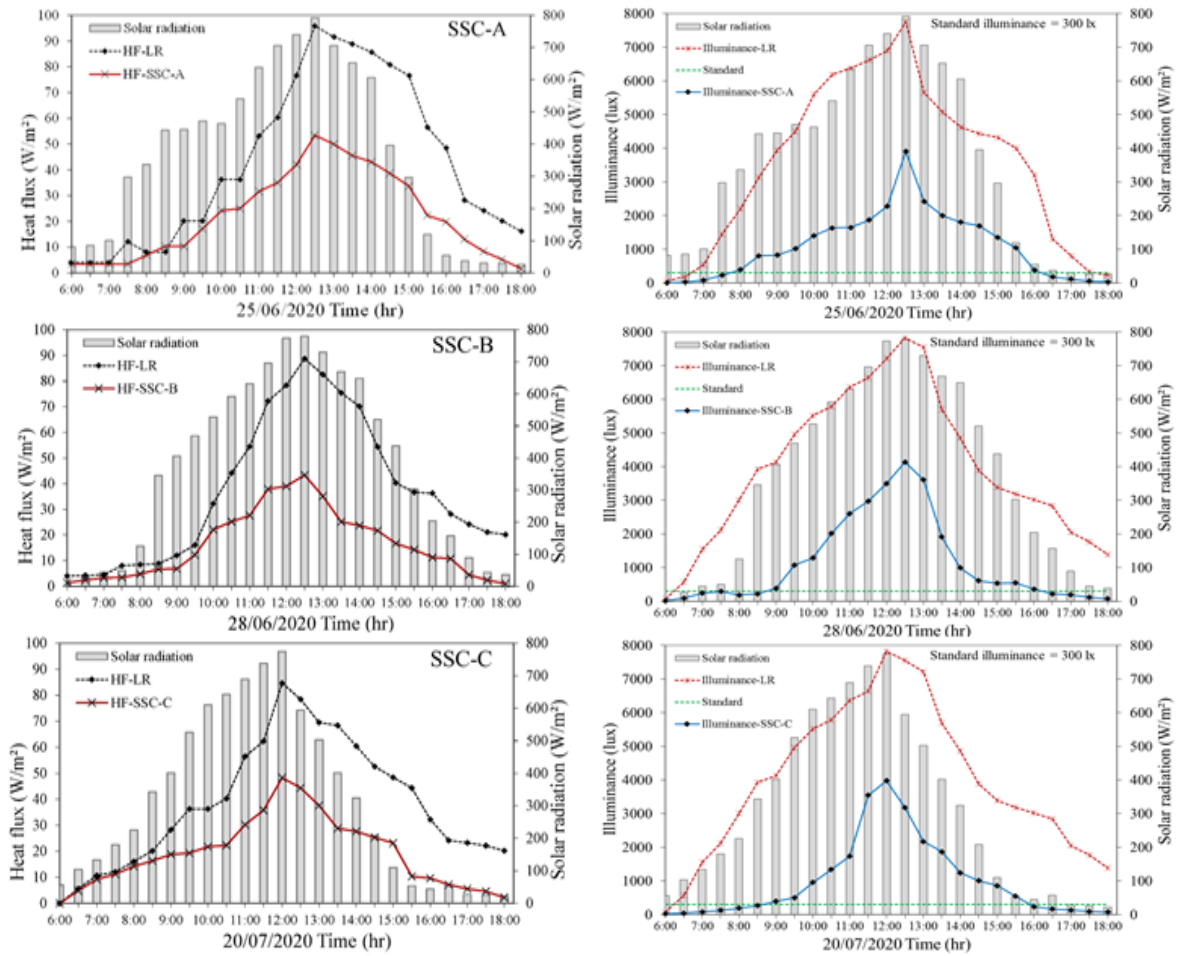


Figure 8. Hourly variation of the measured heat flux through the typical roof and SSC (left) and indoor illuminance (right) compared with solar radiation for the three inlet configurations considered.

Figure 9 shows that the hourly variation of the air change (ACH) of the house with SSC-A and SSC-B house followed well the incident solar radiation; the more is the incident solar radiation the higher the induced ACH. It varied between 2-18 and 2-28 for the SSC-A and SSC-B configurations respectively. With the SSC-B configuration, more air is admitted through the openings leading, therefore, to higher induced ventilation rate. It is worth to mention that the SSC ventilation is also affected by the prevailing wind especially in the case with soffit inlet. That's explain why ACH didn't decrease following the decrease of incident solar radiation in the afternoon as wind was relatively important in the afternoon. For comparison, ACH ventilation performance of BSRC bioclimatic roof with 1.5 m² and only room side inlet opening reported in (Waewsak et al., 2003) varied between 8 to 14. It can be

noticed that our SSC even with smaller surface area could generate significant ACH that's extremely satisfying.

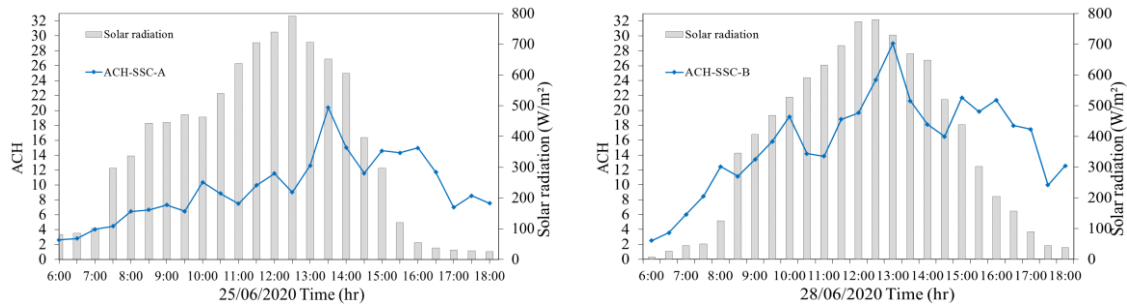


Figure 9. Hourly variation of the air change of SSC house with room inlet configurations.

CONCLUSION

A new modular configuration of roof integrating skylight and solar chimney (SSC) is designed and tested. SSC was composed of three layers: 1 mm thick clear acrylic layer on the outside, a set of aluminium slats 1mm thick distanced each other at the middle and a third layer with a combination of clear acrylic and aluminium slats at the inner side. The dimensions of the SSC are 0.50 m x 1.50 m x 0.15 m. A 0.025 m² outlet opening was located at the top lateral side whereas two inlet openings of similar surface area were installed on the bottom lower layer (one inside the room and another outside). It was found that in all scenarios considered the indoor temperature of room with SSC was 1 to 4 °C lower than that of the reference room and varied following ambient conditions. The measured heat flux transmitted through the roof of reference house was much more important than all SSC scenarios tested; a 50% difference was observed when both SSC inlets were open. SSC could also induce considerable air change in the room varying between 2-28 ACH and reduce indoor illuminance by 50% compared to the reference house. Due to its high performances, simplicity and modular concept, wide integration low-cost roofs seems promising.

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