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Experimental study of a Compact Unglazed Solar Thermal Facade (STF) for Energy-efficient Buildings

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Abstract

This paper presents a real-time experimental measurement of a novel compact unglazed solar thermal facade (STF) system at outdoor environment in Shanghai, China for about a whole summer week. It demonstrates the daily average solar thermal efficiency fluctuated from 40% to 45.5%. The overall result indicates the advantages of the STF with simple structure, low cost and high feasibility in architectural design for energy-efficient building application, especially at future district or city levels.

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Keywords: *Experiment; Solar thermal façade; Energy-efficient;Buildings*

1. Introduction

Recently, the Solar Thermal Facade (STF) systems demonstrate a real sense of integration with building that can be a potential solution for the enhanced solar thermal deployment and reduced operational cost in the contemporary built environment locally, meanwhile being available for building heating, cooling, hot water supply and power production [1]. Even though the STF technology is still in

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the start-up stage, a large number of commercial products and engineering projects can be found in the real world. A state of art review into commercial STF products has been carried out [2-4]. In general, the endeavors of these STF devices can be summarized into three points: i) the enhanced heat transfer capacity with efficient and durable approach; ii) the innovative design in solar technical components with variable choice of colors and textures; and iii) the employment of advanced processing and installation techniques. However, these collectors in essence still have been identified with several inherent problems. The common concerns mainly lie in: 1) bulky size; 2) lower level of flexibility in solar thermal technology; 3) complex structures placement; 4) less choice of different surface treatments, such as texture and colour; 5) overheating risk; 6) relative low optical efficiencies; 7) fewer multifunctional construction elements choice; 8) higher overall cost; and 9) similarity in block and rigid size among most STF products, which definitely require extra more effort for architects to combine as construction materials [5]. As a result, a compact unglazed STF is developed that is lower in overall cost, concise in daily operation and maintenance (O&M) and high flexibility for truly building integration solution so that architecture expression freedom and worksite installation can also be guaranteed, shown in Fig. 1. The plan for a typical STF integrated residential building is illustrated in Fig. 2, indicating the STF combination with bay window, south wall and punched window. Three different STF types are used along the east-south-west orientation, including type 1 curved STF for bay window, type 2 STF with various textures for south wall, and type 3 STF with different colours of light dark and light orange for punched window.

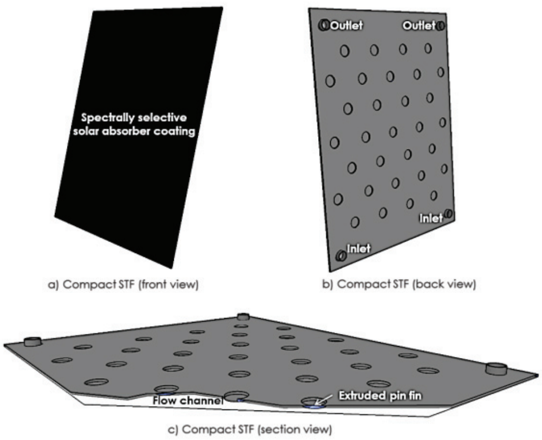

Fig. 1 Concept design of the compact STF panel

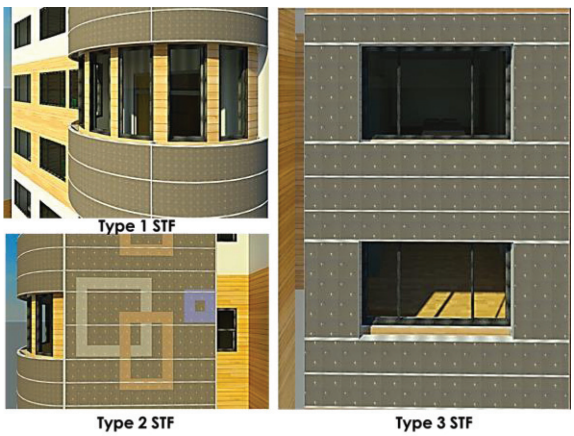

Fig. 2 Three different STF types for building integration

2. Fabrication of the Prototype System

According to the concept design, a STF prototype system has been fabricated at Shanghai Pacific Energy Centre, China. The novel compact STF exploited the stainless steel sheets as the basic material; each sheet was only 1.2 mm thick by considering weight issues for building integration. Then the polypropylene piping system was selected for the STF prototype system connection. The STF prototype, with the dimension of 488 mm× 348 mm, was fixed vertically onto a frame. A magnetic regeneration water pump was installed in the water loop to power the cooling water cross. A water tank of 35 litres with built-in heat exchanging coils was also installed and connected to the circulation loop to obtain heat and store the heating water. The polystyrene board was used as the insulation materials for the STF to minimise the heat loss. An electrical rubber heating plate with the percentage controller, which acts as the equivalent solar radiation source, was closely attained to the external surfaces of the STF. The image of the whole experimental rig of the STF hot water prototype system is presented in Fig. 3.

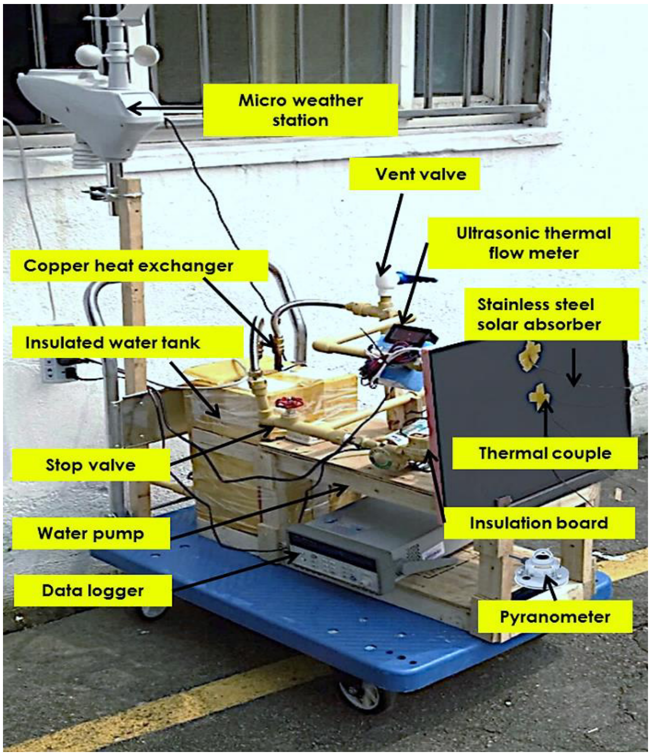

Fig.3 Images of the outdoor STF testing rig

3. Operational performance evaluation in outdoor conditions

Real-time experimental measurement of the proposed STF prototype system has been conducted in the outdoor conditions for about one week, which demonstrates its performance reliability to some extent. Further study should continue on the measurement for the long-term duration (more than 12 months). A preliminary description about the field testing is give as below:

3.1. Outdoor experimental set up

The outdoor experimental rig for the proposed STF system was continuously operated and recorded in the overcast and cloudy weather conditions from 14th to 21st July 2015 in Shanghai, China (31° 11'N and 121° 29'E). Different from laboratory controlled indoor testing, the outdoor testing was fully operated for about eight hours daily. And all the measurement instruments were listed in Table 1. The micro weather station was applied to record the surrounding climate statuses, such as solar radiation, dry bulb outdoor temperature, humidity, wind speed/direction, barometric pressure, precipitation and solar irradiation. All the testing results were recorded at one-hour interval. A number of T-type thermocouples were respectively placed in the inlet/outlet of water loop, the middle of water tank, and the external surface of STF absorber from top to bottom. All these thermal couples were linked to an Agilent 34970A data logger associated with a computer for data recording. Moreover the ultrasonic thermal flow meter was connected into the pipe to measure the instantaneous flow rate.

Table 1 List of fittings and measurement instruments in the testing rig

Component name	Model No.	Description
PP-R water pipe	S3.2DN20×2.8mm	2.8m in length
Stainless steel water pump	15WGO.5-8	100W, 8m hydraulic head:,up to 16 liters/min
Customized stainless steel STF		488×348×5mm
Customized water tank	185×185×370mm, weld by PP boards, inserted with heat exchanger	
Ultrasonic thermal flow meter	YG-RLM(C)	Flow rate range: 0.05-5 m³/h
Customized rubber heating plate	Dimension of 500×400mm with external power regulator	
Micro weather station	Misol WS-HP2K-1	Dry/dew point temperature; humidity; Wind speed/ direction; barometric pressure; precipitation; Lux.
Smart electricity meter	British gas	To measure heating input load
T-type Thermocouple	RS:621-2164	Min/max temperature sensed: -200 ~ 350°C;
Data logger equipment	34970A	10 channels to record data

4. Operational performance results

4.1. Daily performance

The daily temperature of absorber varied from 26.2℃ to 42.8℃ along with the water temperature variation in water tank from 25.5 to 40.1℃ accordingly. In general, the daily average solar thermal efficiency of the STF fluctuated from 40% to 45.5%, with an average of 43.3%. Based on Equation [6], the semi-empirical thermal efficiency can also be expressed with the correlations of both external weather and operational conditions:

$$\eta_{th}= \eta^*_{th}-U_L(T_{in}-T_a)/I \quad [1]$$

where, η^*_{th} is the characteristic module thermal efficiency, and can be interpreted when the temperature of the inlet working fluid (T_{in}) equals to the mean ambient air temperature (T_a). U_L is the overall heat-loss coefficient of the module and I is the incident irradiation. With the measured weather and operational conditions, the values of η^*_{th} and U_L/I for this STF module can be determined by the linear regression analysis. It was found that both the linear coefficient and the intercept were relatively low under this summer operation. It could be identified that the linear coefficient relevant to heat loss coefficient was beneficial from the warmer outdoor temperature range (29.9°C to 32.5 °C in average) and the median wind speed range (0.17 to 1.22 m/s in average), while the intercept relevant to the characteristic module thermal efficiency were attributed to cloudy or overcast weather conditions (166.4 to 325.8 W/m^2 in average). However, the linear coefficient would increase significantly along with extreme weather conditions with lower surrounding air temperature or/and higher wind speed.

$$\eta_{th}=-2.9471(T_{in}-T_a)/I+0.5381 \quad [2]$$

4.2. Instantaneous Performance

Fig. 4 depicted the instantaneous temperature distributions of different system components and the surrounding air in the testing day of 16th July 2015. It was found that all temperature values of the tank water, absorber plate, inlet, and outlet of absorber presented similar general variations along with the change in ambient temperature, being up-rising in the morning and down-falling in the afternoon. The temperature of the tank water grew continuously from 25.5℃ at the beginning to the highest of 37.4℃ around the early afternoon, but finally fell down to 35.℃ at the end of day. This was because higher-temperature working fluid circulated in the loop led to a higher heat loss to surroundings especially after the peak time point of both solar radiation and air temperature, and consequently slightly decreased the water temperature in the water tank. On the other hand, the stainless steel material also contributed partially to the quick response of both heat gain and heat loss for the STF module. This could be mitigated through controlling circulation flow rate, or bypassing the solar circuit to the water tank. In addition, there was an obvious temperature gap between the water tank and the inlet of absorber. It could attribute to the insufficient heat transfer in the internal heat exchanger caused by the implementation of a U-shape pipe as the internal heat exchanger. In terms of temperature distribution in STF absorber, it varied in the range between 29.4℃ to 41.6℃ with a mean value of 38.9℃. The temperature gap between STF surface and the outlet of absorber was about 1.3 to 5.7℃. And the greatest and smallest gaps occurred in the beginning and the middle of the day respectively due to the variations in solar radiation, incidence angle of solar beams and surrounding temperature.

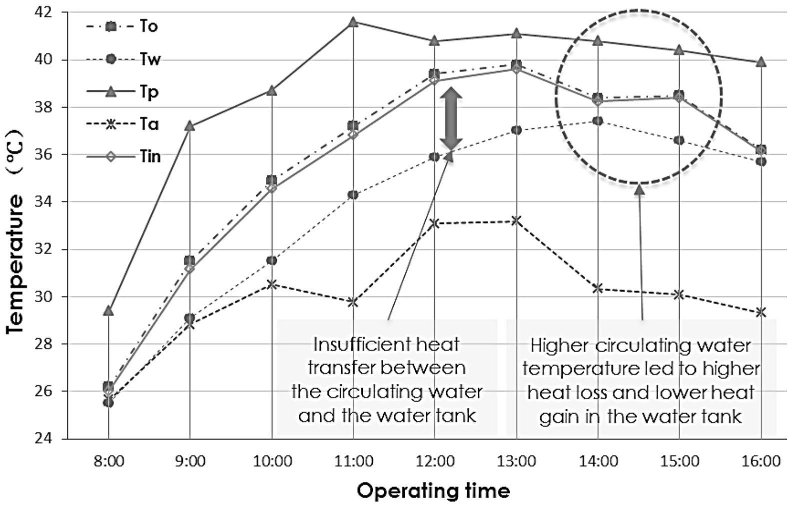

Fig. 4 Temperature variation in different STF components over the testing duration

Fig. 5 illustrated the variations of the STF's thermal output and its corresponding thermal efficiency over the testing duration. The average hourly solar heat output of the STF and the thermal efficiency were 95.4 W/(m^2-h) and 44.8 % respectively. The variation of the STF's thermal output was similar to the variation in the solar radiation, presenting a sharp increasing trend in the morning, and a decreasing trend in the later afternoon. This may be because that the solar thermal efficiency was primarily affected by solar incidence angle, air temperature, and wind speed. Since the magnitudes of wind speed and air temperature change were evenly distributed around 30.1℃ and 1.2m/s, solar incidence angle was the dominating factor in this case. Therefore it led to sharp changes in both solar thermal efficiency and the STF's thermal output. During the remaining operational periods, the above parameters counteracted each other equivalently and enabled a relatively steady thermal efficiency and thermal output.

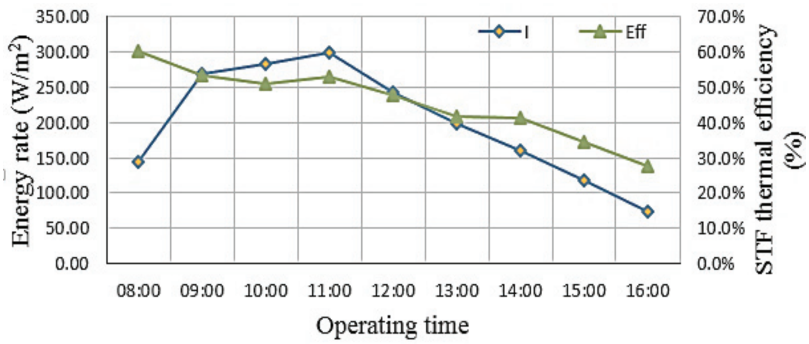

Fig. 5 Variation of solar radiation, useful heat gain, and STF thermal efficiency over the daily testing duration

5. Conclusion

A real-time experimental measurement of the proposed STF prototype system has been carried out at outdoor environment in Shanghai, China for about a whole summer week. It results demonstrates its performance reliability to some extent. The daily average solar thermal efficiency fluctuated from 40% to 45.5%. As for the instantaneous performance, the quick response of both heat gain and heat loss was observed which could be attributed to the stainless steel material; a temperature gap between STF surface and the outlet of STF was found about 1.3 to 5.7℃.

The overall result indicates the proposed STF has the potential in the energy-efficient building application. In terms of STF's energy efficient performance, the integration of the STF into the building can affect the overall building energy performance through changes in the emissivity and the solar absorbance of the original building envelope, and the corresponding temperature difference between the STF module and the original building envelope will reduced, therefore decrease the negative external conduction for built environment.

All of these observations are expected to be further validated through a further study to continue on the measurement with the long-term duration in a complete showcase building (more than 12 months).

Acknowledgements

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References

[1] Zhang X., et al., 2015. Active Solar Thermal Facades (ASTFs): from concept, application to research questions. Renewewable and Sustainable Energy Reviews, 50, pp. 32–63
[2] Spur, R. et al., 2006. Performances of modern domestic hot-water stores. Applied Energy, 83, pp.893–910.
[3] A. Giovanardi et al., 2015. Integrated solar thermal façade system for building retrofit. Solar Energy, 122 , pp 1100–1116
[4] Zhang X. et al., 2015. Building integrated solar thermal (BIST) technologies and their applications: A review of structural design and architectural integration, Journal of Fundamentals of Renewable Energy and Applications 215 (5): 182
[5] Shen J., Zhang X., et al., 2016. Characteristic study of a novel compact solar thermal facade (STF) with internally extruded pin-fin flow channel for building integration, Applied Energy, 168 pp. 48-64.
[6] Duffie, J.A. & Beckman, W.A. 2006. Solar Engineering of Thermal Processes. John Wiley & Sons.