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Experimental study of the water heating performance of a novel tile-shaped dual-function solar collector

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Abstract

Solar collectors are widely used in buildings for energy saving. However, the conventional solar collector does not match the tile roof of the building in appearance. To solve this problem, we propose a novel dual-function solar collector with tile-shaped Polymeric Methyl Methacrylate (PMMA) covers to match the roof appearance. This novel dual-function solar collector can provide hot air in winter and hot water in other seasons, with high annual solar thermal utilization ratio. Experiments are conducted to investigate the performance of the tile-shaped collector. The efficiency of the novel tile-shaped dual-function solar collector varied from 53.2% to 69.1% in water heating mode in the test. The daily thermal efficiency of the water heating system with this tile-shaped collector system varied from 54.0% to 61.8%, while the daily thermal efficiency of the dual-function solar collector with semicircle covers varied from 44.7% to 59.2%, compared with the daily efficiency of the conventional dual-function solar collector without PMMA covers varied from 35.5% to 67.4%. It shows that the tile-shaped collector can greatly integrate the solar collector technology in to the local special feature buildings with slightly decrease of thermal efficiency.

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Keywords: solar collector; dual-function; tile-shaped; water heating performance

1. Introduction

In China, buildings consume about 28% of the whole energy consumption. Utilization of solar energy, especially solar collectors, can significantly reduce the consumption of fossil energy in a building. With sloping roofs, the

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building can be easily integrated with solar collectors. Many researchers investigate the integration of solar collectors with buildings. However, there are some drawbacks in collectors, such as complex structure, unmatched appearance and installation difficulty. Ji [1] and Ma [2] proposed the idea of the dual-function solar collector. Air flow channels are introduced to conventional sheet-and-tube solar water collectors so that the collector can provide heat air in winter.

Referring to the dual-function solar collector, we designed a novel dual-function solar collector with tile-shaped Polymeric Methyl Methacrylate (PMMA) covers, which has a good match with the local special feature building culture. This novel collector can provide air heating in cold winter and water heating in other seasons, thus increasing the annual utilization ratio and solar thermal efficiency. Experiments were conducted to investigate the water heating performance. Conventional dual-function solar collector without tile-shaped covers was used as a contrast.

Nomenclature

A_a	collector aperture area, m^2
c_p	specific heat capacity of the water, J/(kg K)
G	daily solar irradiance, MJ/(m^2 day)
$\dot{m}$	water mass flow rate, kg/s
S	solar irradiance, W/m^2
T_a	ambient temperature, ^oC
T_{final}	final water temperature in tank, ^oC
T_{in}	inlet water temperature, ^oC
$T_{initial}$	initial water temperature in tank, ^oC
T_{out}	outlet water temperature, ^oC
V_s	volume of the water tank, L
η_i	instantaneous water heating efficiency,-
η_d	daily water heating efficiency,-
ρ_w	density of air, kg/m^3

2. Description of the tile-shaped collector and the experimental setup

2.1. Description of the tile-shaped dual-function collector

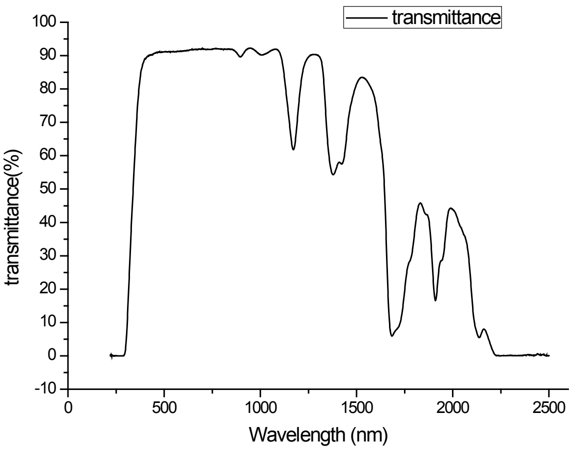

Fig.1. transmittance of 5mm PPMA plate in different wavelength

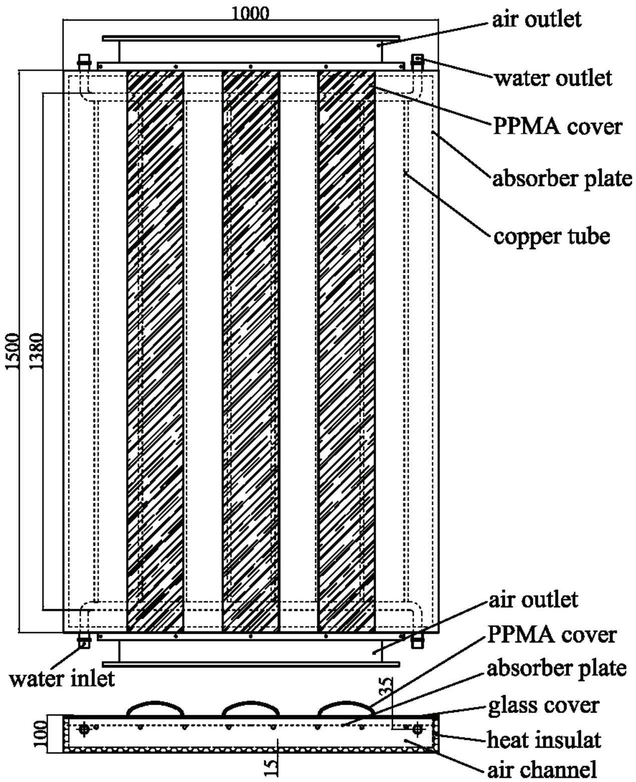

Fig.2. configuration diagram of the collector with tile-shaped PPMA covers


Fig.3. collectors with 2 types of PMMA covers and tile-shaped collectors mounted on the piched roof

The collector consist of the following components: tile-shaped PMMA covers, glass cover, aluminium absorber plate, copper tubes, air inlet, air outlet and insulation layer. The collector has aperture area of 1.375 m^2 and an air gap between the glass cover and the absorber plate. Eight copper tubes are leaser welded to the lower surface of the absorber plate. In air heating mode, the tubes are closed. The air flow through the collector along the gap and be heated by the absorber plate. In water heating mode, the inlet and outlet of the air flow channel are closed. Both semicircle and tile-shaped PMMA covers are used. The light transmittances of different wavelength throughout the 5mm PMMA plate were measured with a spectrometer (DUV-3700) and is shown in fig.1. It can be seen that the transmittance of the PMMA plate for solar energy is about 90%. Configuration diagram and photos of the tile-shaped collector are shown in fig.2 and fig.3.

2.2. Experimental setup

In water heating mode, the thermal efficiency and the daily thermal efficiency are tested. In thermal efficiency test, the collector works with a constant water flow which is driven by a brushless DC pump. In daily thermal efficiency test, a thermo-siphon solar water heating system with a 150 L water tank is used.

The test rigs are built in Hefei (32°52'N, 117°17'E). The tilted angle of the collectors is fixed at 35°. The instruments used in the test is shown in Table 1. Five T-type (copper-constantan) thermocouples are installed evenly vertical-distributed in the water tank to measure the water temperature. All the data are collected by a data logger every ten seconds. The test procedures are referred to the recommendation of ASHRAE 93-2010[3].

Table 1. List of experimental testing and monitoring devices.

Device	Specification	Accuracy
Pyranometer	TQB-2	2%
Thermocouple	Type T (coper-constantan)	±0.5°C
Spectrometer	DUV-3700	0.3%
Data acquisition	34970A	

2.3. Performance evaluation

2.3.1. Thermal efficiency

In steady state condition, the thermal energy gain is the enthalpy increase of the flow water between outlet and inlet, expressed as [4]

$$Q_u = \dot{m}c_p\Delta T = \dot{m}c_p(T_{out} - T_{in}) \tag{1}$$

The thermal efficiency of the tile-shaped collector is the heat gain of the water divided by incident solar radiation as [5]

$$\eta_i = \frac{Q_u}{A_a S} = (\frac{\dot{m}c_p}{A_a S})(T_{out} - T_{\mathrm{in}}) \tag{2}$$

2.3.2. Daily thermal efficiency

The test is conducted on sunny days from 8:00 am to 4:00 pm. The thermal energy gain is the heat accumulated by the water in the tank, calculated as

$$Q_s = \rho_w c_p V_s (T_{final} - T_{initial}) \tag{3}$$

The daily average efficiency can be calculated as the following,

$$\eta_d = \frac{Q_s}{A_a G} = (\frac{\rho_w c_p V_s}{A_a G})(T_{final} - T_{initial}) \tag{4}$$

3. Results and discussions

Table 2. Instantaneous water heating efficiency of the collector with semicircle covers under different conditions

Time	T_{in}(°C)	T_{out}(°C)	ΔT(°C)	T_a(°C)	$S(W/m^2)$	$\dot{m}(Kg/s)$	T_{in}^*	η(%)
10:56	19.7	23.7	4.0	22.8	808.5	0.046	0.00346	69.1
12:34	30.8	34.9	4.1	23.1	868.3	0.045	0.00811	64.6
12:44	33.9	37.8	3.9	24.1	854.6	0.046	0.01044	63.1
13:23	27.1	31.1	4.0	25.0	823.6	0.044	0.00232	65.5
14:58	40.5	43.1	2.6	24.5	692.4	0.047	0.02116	53.2
11:15	26.2	29.7	3.5	25.1	849.4	0.054	0.00122	67.7
12:13	26.3	29.7	3.4	21.8	870.6	0.055	0.00473	64.9
13:00	39.1	42.9	3.8	25.2	848.5	0.041	0.01493	55.5
13:20	27.1	31.2	4.1	24.4	829.2	0.043	0.00295	65.8
13:26	27.1	31.0	3.9	24.5	803.7	0.044	0.00288	64.7
14:28	40.5	43.7	3.2	25.3	714.6	0.040	0.01944	54.1
14:58	40.6	43.7	3.2	25.0	707.5	0.042	0.02011	56.6

Table 3. Daily efficiency of the collector without PMMA covers

Date	$\overline{T}_a$(°C)	T_{inital}(°C)	T_{final}(°C)	ΔT(°C)	$G(MJ/m^2)$	T_{inital}^*	η(%)
2014/5/27	28.8	24.1	47.7	23.6	17.8	-0.263	60.2
2014/7/8	27.8	19.2	44.4	25.2	17.0	-0.504	67.4
2014/7/9	28.7	21.8	43.8	22.1	15.7	-0.440	63.8
2014/7/14	25.1	22.0	43.3	21.4	16.5	-0.187	58.8
2014/7/15	25.4	38.3	50.1	11.8	15.1	0.853	35.5
2014/7/21	34.3	27.0	50.8	23.8	17.5	-0.417	61.8
2014/7/22	36.8	32.7	58.2	25.6	20.0	-0.205	58.1
2014/7/23	38.9	33.6	60.1	26.5	20.4	-0.258	58.9
2014/7/29	32.6	28.2	52.9	24.7	19.0	-0.233	59.2
2014/7/30	35.4	29.5	57.1	27.6	21.1	-0.280	59.7

Table 4. Daily efficiency of the collector with semicircle PMMA covers

Date	$\overline{T}_a$(°C)	T_{inital}(°C)	T_{final}(°C)	ΔT(°C)	$G(MJ/m^2)$	T_{inital}^*	η(%)
2014/5/12	23.4	15.5	41.1	25.6	20.1	-0.392	57.9
2014/5/28	32.6	25.2	47.9	22.7	17.8	-0.414	58.0
2014/6/6	27.7	22.4	39.9	17.5	14.0	-0.382	56.7
2014/6/7	27.7	24.0	33.7	9.7	7.4	-0.504	59.2
2014/6/8	28.8	32.3	44.3	12.0	12.2	0.287	44.7
2014/6/9	29.1	24.2	44.3	20.1	16.7	-0.295	54.9
2014/6/10	31.2	24.9	48.8	23.9	19.6	-0.321	55.4
2014/6/11	31.3	26.2	48.9	22.6	18.5	-0.278	55.8
2014/6/12	31.2	36.0	54.2	18.2	17.3	0.275	47.9
2014/6/13	32.1	28.4	46.6	18.2	14.8	-0.247	55.9

Table 5. Daily efficiency of the collector with tile-shaped PMMA covers

Date	$\bar{T}_a(^\circ C)$	$T_{inital}(^\circ C)$	$T_{final}(^\circ C)$	$\Delta T(^\circ C)$	$G(MJ/m^2)$	T^*_{inital}	$\eta(\%)$
2014/9/21	25.7	19.3	45.5	26.2	19.4	-0.331	61.6
2014/9/22	28.2	23.8	48.3	24.5	19.5	-0.229	57.3
2014/9/25	27.8	24.3	38.5	14.3	10.5	-0.339	61.8
2014/10/3	27.5	23.4	45.1	21.7	17.0	-0.242	58.0
2014/10/4	27.2	23.0	50.1	27.1	21.4	-0.194	57.7
20.14/10/5	28.5	23.4	46.9	23.4	18.0	-0.286	59.4
2014/10/7	22.8	21.6	46.4	24.8	21.0	-0.058	54.0

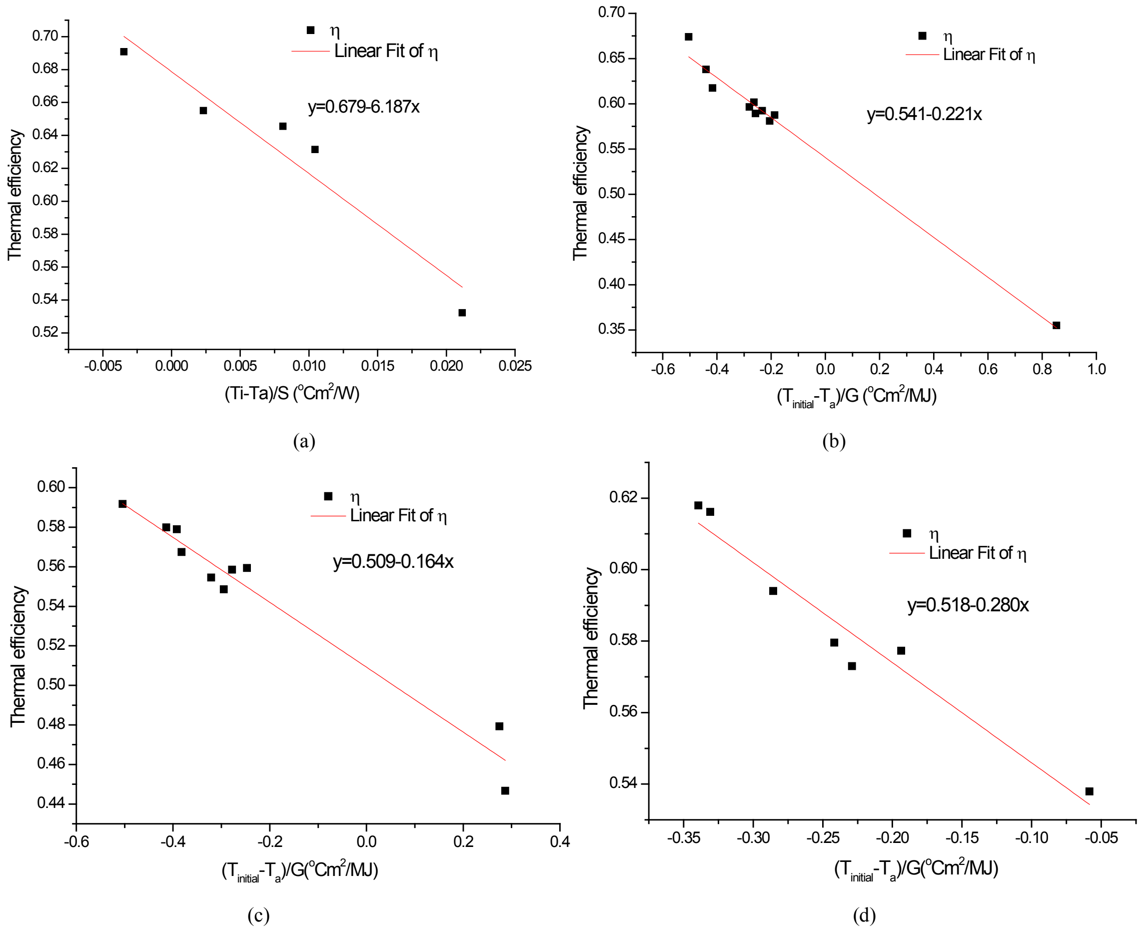

Fig.4. (a) plot of instantaneous thermal efficiency of collector with semicircle covers;
(b) plot of daily thermal efficiency of collector without PMMA covers;
(c) plot of daily thermal efficiency of collector with semicircle covers;
(d) plot of daily thermal efficiency of collector with tile-shaped covers;

The instantaneous performance tests were carried out under quasi-steady-state conditions in the midday hours of April 29th 2014. The efficiency under different inlet temperature and different flow rate was tested. The performance data are shown in table 2. The curve of η_i against $(T_{in}-T_a)/S$ is shown in fig.4 (a). Thermal efficiency can expressed with regression line:

$$\eta=0.679-6.187(T_{in}-T_a)/S \quad (5)$$

The full-day tests of the 3 types of dual-function solar collectors working in water heating mode were conducted from May, 2014 to October, 2014. The daily water heating efficiency of the tile-shaped collector system varied from 54.0% to 61.8% as shown in table 5, the daily efficiency of the dual-function solar collector with semicircle covers varied from 44.7% to 59.2% as shown in table 4, and the daily efficiency of the conventional dual-function solar collector without PMMA covers varied from 35.5% to 67.4% as shown in table 3.

Daily efficiencies of collectors without PMMA covers, with semicircle covers and with tile-shaped covers are shown in fig.4 (b),(c),(d) separately. The efficiencies are successively expressed as:

$$\eta=0.541-0.221(T_{initial}-T_a)/G \quad (6)$$

$$\eta=0.509-0.164(T_{initial}-T_a)/G \quad (7)$$

$$\eta=0.518-0.280(T_{initial}-T_a)/G \quad (8)$$

The standardized efficiency of the collector with tile-shaped covers is 51.8% in contrast to 54.1% of the collector without PMMA covers and 50.9% of the collector with semicircle covers. It's obvious that the efficiency of the collectors with PMMA covers are slightly lower than which without PMMA covers. The reason is that the added PMMA covers reduce the transmittance of solar energy.

4. Conclusions

A novel tile-shaped dual-function solar collector is proposed and constructed in this paper. The collector can generate hot water or hot air in two different modes. Its tile-shaped appearance matches the pitched tile roofs. The water heating performance of the collector was investigated by experiment under different conditions compared with other 2 collectors without PMMA covers and with semicircle covers. The results are as follows:

- The instantaneous efficiency of the novel tile-shaped dual-function solar collector varied from 53.2% to 69.1% in water heating mode depending on the ambient condition and flow rate. The standardized instantaneous efficiency of semicircle cover collector is 67.9%.
- The daily water heating efficiency of the tile-shaped collector system varied from 54.0% to 61.8%, and the standardized efficiency is 51.8%
- The daily efficiency of the dual-function solar collector with semicircle covers varied from 44.7% to 59.2%, and the standardized efficiency is 50.9%
- The daily efficiency of the conventional dual-function solar collector without PMMA covers varied from 44.7% to 59.2%, and the standardized efficiency is 54.1%

The novel tile-shaped PMMA covers can promote the aesthetic characteristic of the collector and match the tile roof in appearance. As a sacrifice, the water efficiency of the collector will have an acceptable decrease.

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