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Experimental investigation of the higher coefficient of thermal performance for water-in-glass evacuated tube solar water heaters in China

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ABSTRACT

Solar water heaters (SWHs), now widely used in China, represent an environmentally friendly way to heat water. We tested the performance of more than 1000 water-in-glass evacuated tube SWHs according to Chinese standards and found that the heat loss from the storage tank and capacity of the solar collector affected their thermal performance. The optimum parameters to maximize the performance of water-in-glass evacuated tube SWHs included a ratio of tank volume to collector area of 57–72 L/m^2, which should give a system efficiency of 0.49–0.57, meaning that the temperature of water in the tank will exceed 45 °C after one day of heat collection. In addition, the polyurethane insulation layer should be around 50 mm thick with a free foaming density of about 35 kg/m^3, and the evacuated tube should be short. The tilt angle did not affect the performance of the SWHs. These results should aid in the design of highly efficient SWHs.

1. Introduction

China is a country that produces and consumes a vast amount of energy, and with its rapid economic growth, it is anticipated that its energy consumption will increase similar to the situation in countries including Jordan and Tunisia [1,2]. The emission of greenhouse gases from China has also increased, and its dependence on imported crude oil increased from 32% in 2000 to 57% in 2012 [3]. However, China has abundant solar energy, which represents an attractive clean energy source.

In China, solar thermal conversion systems have been studied for more than 30 years. During the last decade, the solar thermal industry has developed rapidly. By the end of 2012, around 257,000,000 m^2 of solar water heaters (SWHs) were in use in China, 90% of which were water-in-glass evacuated tubes SWHs [4], as shown in Fig. 1.

To encourage the application of SWHs, from June 1st 2012 to May 30th 2013, the Chinese government provided financial support for the purchase of high-efficiency SWHs, where the amount of the subsidy related to the type of SWH, storage tank volume and energy grades of the SWH [5]. The Chinese national standard GB26969-2012 specified the relationship between the energy grades and the coefficient of thermal performance (CTP) of the SWH, the latter being related to the thermal performance [6]. Many researchers have undertaken significant studies investigating and evaluating the performance of SWHs both experimentally and theoretically [1,2,7–16]. Çomakl et al. optimized the size of solar collectors and storage tanks to design more economic and efficient solar water heating systems, according to Turkish conditions and relevant Turkish standards, with experiments and simulations [7]. Govind et al. identified possible and feasible designs on collector area vs. storage volume using a methodology called the design space approach [8]. The work done by Çomakl and Govind implies the collector area and storage volume affect the thermal performance of a forced circulation solar water heating system with flat plate solar collectors. A report from IEA gives the performance of 11 evacuated solar heating and cooling systems. The heat extraction methods from the evacuated tubes were heat-pipes, U-tube inserts or integrated collector/storage in the tube [9]; however, the most successful method was the simple water-in-glass concept [10]. A case study by Hazami et al., in the Tunisian market, shows that a forced circulation system with evacuated tube solar collectors had a better performance and cost benefits than a system with flat plate solar collectors [2,11]. The experimental work by Sakhrieh and Al-Ghadoor in the Jordanian market indicated that evacuated solar collectors had the highest efficiency of five types of solar collectors [1]. Hayek et al. in the Lebanese market, compared two types of evacuated tube solar collectors, and the results showed

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Nomenclature

Ac	contour aperture area, m^2
c_{pw}	specific heat at constant pressure, kJ/(kg °C)
CTP	the coefficient of thermal performance of a solar water heater
H	daily solar radiation of the test day, MJ/m^2
k	the coverage factor
m	heat water mass in the water tank, kg
RAV	ratio of solar water heater tank volume to collector area, L/m^2
$Q_s(e)$	daily useful heat gain of the contour aperture area of the solar water heater under the tested conditions, MJ/m^2
$Q_s(m)$	minimum value of daily useful heat gain of the contour aperture area of the solar water heater specified in GB/T 19141-2011 [17], MJ/m^2
$t_{as(av)}$	average surrounding air temperature during the heat loss test, °C
t_b	initial temperature in the storage tank when the test starts, °C
t_e	final temperature in the storage tank after the test finishes, °C
t_f	final temperature in the tank after the heal loss test, °C
t_i	initial temperature in the tank at the beginning of the heat loss test, °C
u_r	relative uncertainty
U_s	average heat loss coefficient of the solar water heater under the tested conditions, W/K
$U_{sl}(e)$	average heat loss coefficient of the solar water heater under the tested conditions, $W/(m^3\,K)$
$U_{sl}(M)$	maximum average heat loss coefficient of the solar water heater specified in GB/T 19141-2011 [17], $W/(m^3\,K)$
V	available water volume contained in storage tank, m^3

Greek symbols

α	weighted average heat loss coefficient in coefficient of thermal performance of a solar water heater
ρ_w	water density (kg/m^3)
η	solar water heater system efficiency (%)
$\Delta\tau$	duration of the heat loss test (s)

Abbreviations

AM	air mass
GB	Chinese compulsory national standard
GB/T	Chinese recommended national standard
IEA	international energy agency
ISO	international organization for standardization
SWH	solar water heater

that heat-pipe-based collectors performed better than the water-in-glass design, but the payback periods for water-in-glass collectors were relatively short [12]. In the Hong Kong market, performance evaluation results showed that the two-phase (heat-pipe) closed thermosyphon system was a slight improvement on the single-phase (water-in-glass) open thermosyphon system with the draw-off profile from the IEA-SHC Task 26 recommendations [13], but the payback times were the same despite the higher cost of the two-phase thermosyphon system [14]. Morrison et al. have performed in depth studies on water-in-glass collectors and SWHs. They developed the procedure for simulating the performance of water-in-glass SWHs with anti-reflectors under the tube array. The simulation results indicated that the same preheat water-in-glass SWH with a larger tank resulted in a slight decrease in annual solar fraction in a Sydney location. They also developed a numerical model of heat transfer fluid flow inside a water-in-glass evacuated tube, and established that the flow rate was influenced by the radiation intensity falling onto the absorber surface, and the tank temperature [10,15,16]. All the work done by Morrison's groups was related to water-in-glass SWHs with a diffuse reflector underneath the evacuated tube array.

Fig. 1. Water-in-glass evacuated tube solar water heater.

Most of the SWHs now in used in China employ water-in-glass evacuated solar collectors without reflectors [4]. From May 2012 to June 2013, the National Center for Quality Supervision and Testing of Solar Heating Systems (Beijing), one of the largest third party testing laboratories authorized in China by the China National Accreditation Service Conformity Assessment, completed the performance testing of more than 1000 sets of SWHs, most of which were water-in-glass evacuated tube systems without reflectors. We report here on the findings of this testing, which should assist in improving the thermal performance of SWHs.

2. Testing method and equipment

2.1. Testing method

In GB 26969-2011, the *CTP*s for different types SWH are given,as shown in Table 1 [6].

From Table 1, the energy grades of SWHs are directly related to the *CTP*, which can be expressed as:

$$CTP = Q_s(e)/Q_s(m) - \alpha U_{sl}(e)/U_{sl}(M) \quad (1)$$

where CTP is dimensionless, $Q_s(e)$ is the daily useful heat gain of the contour aperture area of the SWH under the test conditions in MJ/m^2, $Q_s(m)$ is the specified minimum value of daily useful heat gain of the contour aperture area of the SWH in MJ/m^2, α is the weighted average heat loss coefficient in CTP of the SWH (dimensionless, here $\alpha = 0.9$ for all SWHs), $U_{sl}(e)$ is the average heat loss coefficient of the SWH under the test conditions in $W/(m^3\,K)$, and $U_{sl}(M)$ is the specified maximum average heat loss coefficient of the SWH in $W/(m^3\,K)$.

The specified values for $Qs(m)$ and $Usl(M)$ in GB/T 19141-2011 [17] are shown in Table 2. For $Qs(m)$ in the Table 2, the value is the minimum requirement, the tested value of $Q_s(e)$ was bigger than $Qs(m)$,while conversely the test value of $U_{sl}(e)$ was smaller than $Usl(M)$.