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Water-in-glass evacuated tube solar water heaters

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Abstract

Evacuated tube solar collectors have better performance than flat-plate solar collectors, in particular for high temperature operations. A number of heat extraction methods from all-glass evacuated tubes have been developed and the water-in-glass concept has been found to be the most successful due to its simplicity and low manufacturing cost. In this paper, the performance of a water-in-glass evacuated tube solar pre-heater is investigated using the International Standard test method ISO 9459-2 for a range of locations. Factors influencing the operation of water-in-glass collector tubes are discussed and a numerical study of water circulation through long single-ended thermosyphon tubes is presented. Preliminary numerical simulations have shown the existence of inactive region near the sealed end of the tube which might influence the performance of the collector.

1. Introduction

Evacuated tube solar collectors have been commercially available for over 20 years, however, until recently they have not provided any real competition to flat plate collectors. Evacuated tube solar collectors based on single envelope vacuum tubes with heat-pipe energy removal have been commercialised in Europe and all-glass evacuated tubes with a U-tube heat removal system have been successful in Japan. Recently there has been a major expansion of the evacuated tube solar water heater market as a result of the development in China of low cost sputter coaters for producing the absorber surface on all-glass evacuated tubes (Yin et al., 1997). Production of all-glass evacuated tubes in China was estimated to be more than 20,000,000 tubes/year in 2001. The majority of these tubes were used in domestic water heaters based on the water-in-glass concept, which is the subject of this paper.

2. Evacuated tube solar collectors

Evacuated tube solar collectors minimise convective heat loss by placing the solar absorbing surface in a vacuum. Radiation heat loss is also minimised by using a low emissivity absorber surface. The problem with the design of evacuated tube collectors is that it is difficult to extract heat from a long thin absorber contained in a vacuum tube. Methods used to extract heat from evacuated tubes include:

- *Heat pipe*: a metal absorber is mounted in a single envelope vacuum tube and the absorber is attached to a heat pipe that penetrates the vacuum space via a glass-to-metal seal.
- *Flow through absorber*: a single ended metal absorber pipe is mounted in a glass vacuum tube through a glass-to-metal seal. A central tube is used to deliver heat removal fluid to the bottom of the metal absorber tube; this then flows up the annular space between the central tube and the larger metal absorber tube. Due to differential expansion the metal tube can only contact the glass at one end unless a vacuum bellows seal is used. An alternative configuration of this concept is to use two small diameter glass-to-metal seals at one end of a single envelope evacuated

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Nomenclature

Q_u	useful energy gain, MJ/day
T_{wi}	tank temperature at the start of the day, K
G	irradiation level, MJ/m^2
T_a	ambient temperature, K
a_1, a_2, a_3	coefficients used in system performance Eq. (1) in, determined from least squares fitting on the daily experimental data
T	Lighthill parameter to predict the existence of stagnant region at the bottom end of an open thermosyphon
Ra	Rayleigh number based on the radius of the tube
θ	tube inclination from vertical
L/r	aspect ratio of the tube

tube. A U-shaped heat removal fluid tube is introduced through the two seals and attached to the absorber.

- *All-glass tubes*: a Dewar type vacuum tube with the solar absorbing surface on the vacuum side of the inner glass tube. The absorbed heat is conducted through the inner glass tube wall and then removed by a fluid in direct contact with the inner glass tube or by heat removal fluid in a metal U-tube inserted in the inner tube with a fin connecting the outlet arm of the U-tube to the inner glass tube.
- *Storage absorber*: Vacuum tubes greater than 100 mm diameter can function as both the absorber and the insulated hot water store. Tubes with 10–20 l of storage have been developed.

Evacuated tubes can also incorporate concentrating surfaces inside or outside the vacuum envelope.

Currently all these types of tubes are commercially available except for the flow through U-tube with two glass-to-metal vacuum seals. The only configurations with demonstrated long life under transient outdoor conditions are the all-glass tube and the heat pipe tube. Configurations that incorporate glass-to-metal seals are expensive and the seal must be protected from shock loading due to internal thermal transients or physical impact due to hail. Systems that transfer the heat removal fluid through a glass-to-metal seal are particularly susceptible to damage due to thermal shock when cold fluid enters a hot tube. The glass-to-metal seal in the heat pipe system is partially protected from thermal shock problems, as the cold heat removal fluid does not pass through the glass-to-metal seal. The all-glass tube is the simplest and cheapest configuration, however, it is difficult to extract the heat from the long glass absorber. The water-in-glass concept in which water is circulated directly through the inner glass tube has good heat transfer from the glass absorber to the heat removal fluid, however, the operating pressure of the heat removal fluid is limited to a few metres of water head. The all-glass tube with the U-tube heat removal system has been successfully used for more than 20 years; however, it is expensive as a result of the plumbing and heat transfer fin in each evacuated tube. The efficiency of this system depends on the quality of the contact between the heat transfer fin and the glass absorber.

2.1. Evacuated tube solar water heaters

Evacuated tube collectors can be used in solar water heaters with either pumped or thermosyphon circulation between the solar absorber array and the storage tank. The all-glass tube with a large diameter metal insert tube can also be used with air as the heat removal fluid. The plumbing network required for all-glass tubes with pressurised working fluid is shown in Fig. 1. The fin inside the tubes must make good contact with the glass absorber and the fluid tubing. For this configuration the low cost of the all-glass tube is countered by the cost of the small-diameter finned tubing required inside each evacuated tube. Fig. 2 shows a photo of water-in-glass evacuated tube solar water heaters in China. The most common system is a 150 l horizontal tank with 20 evacuated tubes. In these systems the evacuated tube is

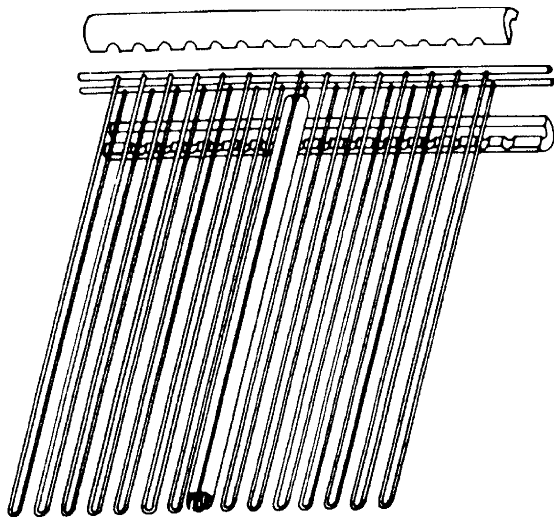

Fig. 1. U-tube and heat removal fin used for pressurised all-glass evacuated tube solar collector.

Fig. 2. Water-in-glass solar water heaters in China.

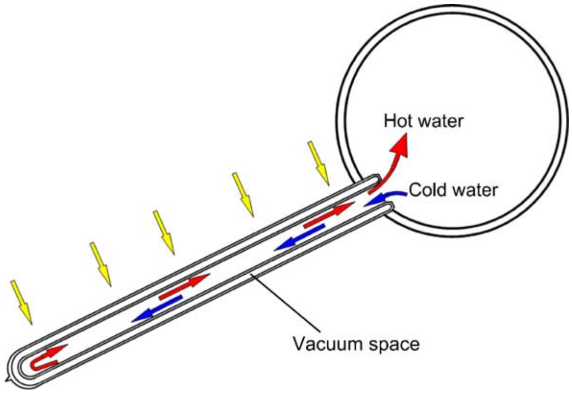

Fig. 3. Cross-section of water-in-glass solar water heater.

inserted directly into a low-pressure water tank as shown in Fig. 3. This configuration is now the most widely used evacuated tube solar water heater. The majority of the market is in China, however, export of these products to other countries is now expanding rapidly. Optimisation of this product is the subject of the research project outlined in this paper.

2.2. Performance of water-in-glass evacuated tube solar water heaters

The majority of water-in-glass solar water heaters are used as solar pre-heaters or as stand-alone water heaters. In China the systems are used as standard low-pressure hot water heaters or as falling level systems. In a falling level system the tank is filled in the morning and then emptied in the evening through a single plumbing connection to the bottom of the tank. The performance of a commercial version of this type of water heater was evaluated using the pre-heater test method specified in International Standard ISO 9459-2 (1994). During this test the system is allowed to operate throughout the day without water draw-off. The tank temperature rise over the day is measured and the useful energy gain (Q_u) is correlated using the performance model given in Eq. (1). The temperature of the tank at the start of the day (T_{wi}) is varied and data for useful energy gain is collected for a range of irradiation levels (G) and ambient temperature (T_a) conditions.

$$Q_u = a_1 + a_2 G + a_3 (T_{wi} - T_a) \quad (1)$$

The system that was tested used a 180 l horizontal tank with 21 evacuated tubes connected directly to the tank. The two glass tubes making the vacuum gap had diameters of 47 and 37 mm and the absorber surface on the inner tube was 1400 mm long. The tubes were spaced 1.49 diameters apart and inclined at 45° over a diffuse anodised aluminium reflector. Daily performance was measured for initial tank temperatures ranging from ambient temperature to ambient +30 °C and daily irradiation levels on the 45° slope of the tube array ranging up to 26 MJ/m^2 day.

The tank was used as a calorimeter to determine the net energy gain each day (after tank heat loss). In the morning the tank was mixed by a small circulating pump and the initial temperature adjusted to the required value. At sunset the tank was mixed again and the useful energy gain determined from the increase of tank temperature over the day and the mass of water in the tank at the end of the day. The water content of the 21 tubes (1.28 l/tube) was included as part of the tank volume. Daily test results are shown in Fig. 4. The correlation coefficients for the ISO 9459-2 model are $a_1 = 0.597$, $a_2 = 1.066$, $a_3 = -0.208$. The measured daily useful energy and the energy determined from the correlation model are compared in Fig. 5. The correlation model shows a good fit to the measured data. The annual

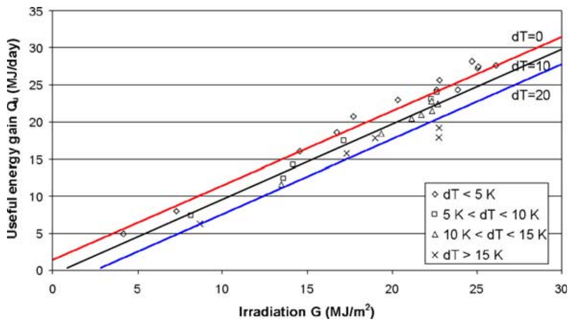

Fig. 4. Measured performance and ISO 9459-2 correlation model.

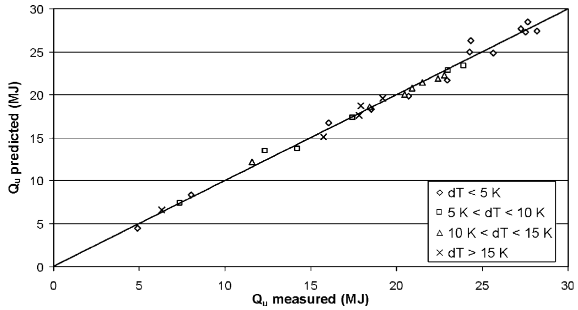

Fig. 5. Comparison of measured daily useful energy and results from the performance correlation.

performance for a given location can be computed from the correlation model and knowledge of the daily irradiation and daytime ambient temperature across the year. The performance of this system for operation as a solar pre-heater delivering an evening only load is shown in Fig. 6 for locations in Australia, China and Europe.

3. Improving the performance of water-in-glass solar water heaters

The performance of water-in-glass evacuated tube solar water heaters depends on the optical efficiency of the tube array, the heat loss of the tubes, the heat loss from the tank and the effectiveness of the heat transfer process from the tubes to the tank. The optical efficiency of the tube array used in this investigation is relatively low as the reflector behind the tube array was simply a flat textured aluminium sheet that covered only 80% of the length of the tubes. Higher optical efficiency could be obtained with a shaped reflector that minimised reflector loss from the gap between adjacent absorber tubes in the array. The fluid transfer process between the tubes and the tank is influenced by two flow limitations. The tubes are inserted into the tank on a 45° diameter plane and as a result thermosyphon circulation between the tubes and the tank cannot penetrate to the bottom of the tank. For the tube inclination of 45° used in this project only 9% of the tank volume is below the level of the tube insertion point in the tank as the system was designed for application in northern regions of China where the latitude it greater than 40°. For lower tube inclination the fraction of the tank volume not directly heated by flow through the evacuated tubes increases significantly.

4. Flow structure in a water-in-glass evacuated tube

The first step of the evaluation of flow in an evacuated tube is to study the flow inside a cylindrical open thermosyphon for various heating conditions. Lighthill (1953) presented an analytical study of vertical thermosyphons for laminar and turbulent flow and identified three basic flow regimes for uniform wall temperature. In order of increasing aspect ratio of the tube, the regimes are; boundary layer flow, similarity regime and similarity regime with a stagnant region near

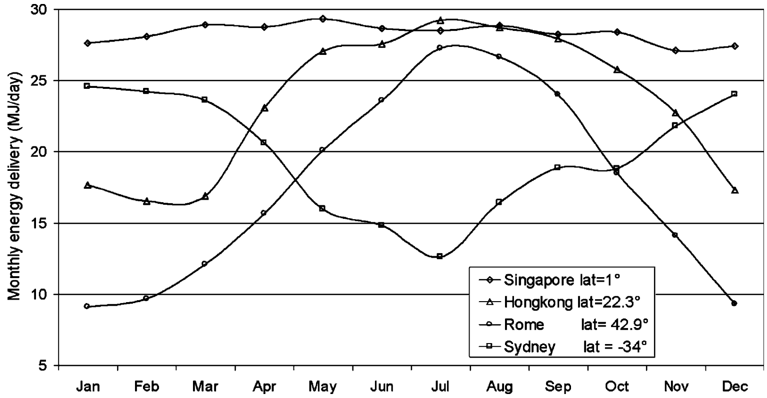

Fig. 6. Daily energy delivery of a water-in-glass solar water heater starting with a cold tank at the beginning of each day.

the closed end. In relation to water-in-glass evacuated tubes a stagnant region would result in an inactive section of the tube. Lighthill defined a parameter T which predicts the existence of a stagnant region as

$$T = Ra(L/r)^{-1}\cos\theta \tag{2}$$

where Ra is Rayleigh number based on the radius of the tube, L/r is the aspect ratio of the tube and θ is the angle of inclination from vertical. According to Lighthill, if T is less than 350, then a stagnant region forms. Stagnant regions in evacuated tubes have been observed experimentally by Behnia and Morrison (1991).

4.1. Numerical model

A computational fluid dynamics package, Fluent V5.4, was used in this analysis. The geometry considered was an open cylinder, inclined at 45° to the vertical. This has also been used in previous studies by Behnia and Morrison (1991) and Gaa et al. (1996) who investigated isothermal boundary conditions on the sidewall of the cylinder. In the present study, two heating schemes were used, uniform wall heating and differential wall heating. In uniform wall heating, both the top and the bottom halves of the cylinder wall have the same temperature. In differential wall heating, different temperatures are used on the top and the bottom halves of the cylinder. A constant pressure boundary condition was applied at the orifice (open end of the cylinder). In reality, tubes in a solar collector receive radiation directly from the sun, as well as from the reflectors underneath that results in variable heat flux around the absorber tube wall. To simulate this condition in the model the sidewall was divided into 32 small, longitudinal sections, each of which has different magnitude of heat flux. The heat flux varies from maximum of 1000 W/m^2 at the top and bottom sections, to the minimum of zero at the side (corresponding to normal incidence solar irradiation). The effect of a constant heat flux boundary condition has also been investigated. Variations with aspect ratio and Rayleigh number were investigated. In the current study, the modelling considered only laminar flow, with Rayleigh number varying in the order of 10^3–10^4. For temperature variations of less than 5 K, the Boussinesq approximation was used for the density, and for higher temperature changes, the property variations with temperature were taken into account. Preliminary investigations at higher Rayleigh number showed difficulties in numerical convergence, as turbulence starts to develop.

4.2. Numerical results

In general, the flow can be described as bi-filamental. It consists of two main streams, the cool descending fluid and the warm ascending fluid. These two streams co-exist stably with a shear layer between them. Boundary layer flow is the main driving force of the fluid movement. The bulk fluid coming in from the reservoir penetrates down the core of the tube and is drawn into the boundary layer on the heated walls.

For uniform wall heating, there is a layer of hot fluid near the bottom of the sidewall. The incoming cold fluid stream is in the middle, slightly offset towards the bottom due to gravity. The boundary layer flow thus starts to develop from the hot bottom part of the tube. As the fluid is being heated, it swirls from near the bottom, around the sidewall, and forms an outgoing flow at the top section of the tube. For heating only on the top half of the tube wall, the flow is stratified, with the bottom half of the tube consisting mainly of cold inflowing fluid, and the heated fluid flows on top. These flow patterns have been observed experimentally by Behnia and Morrison (1991). For uniform wall heating, a stagnant region is observed near the closed end of the tube for low Rayleigh number and high aspect ratio as shown in Fig. 7. For example, for a tube with aspect ratio of 10, a stagnant region forms when Rayleigh number is less than 3000. For a tube with aspect ratio of 30, the critical Rayleigh number is 13,000. These cases correspond to Lighthill's parameter T of 200–300. However, when a uniform heat flux or a variable heat flux was applied on the tube wall, there is no inactive region, regardless of the Rayleigh number or the aspect ratio of the tube. The boundary condition in an operating water-in-glass evacuated tube would be somewhere between the isothermal and heat flux extremes. The possible presence of a stagnant region in the bottom of the very long tubes (>2.4 m) now entering the market is currently being investigated.

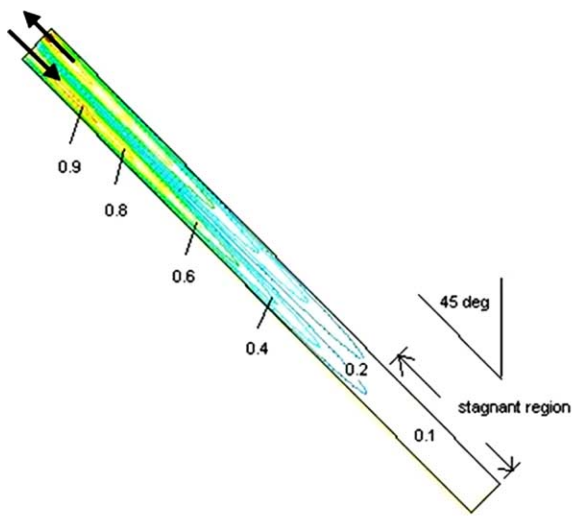

Fig. 7. Normalised velocity distribution in a single-ended evacuated tube, showing a stagnant region in the bottom of the tube ($V_{max} = 4.1$ m/s).

5. Conclusions

Water-in-glass evacuated tube solar water heaters have been shown to operate effectively in a range of climatic conditions. Preliminary investigations of flow conditions in very long tubes have shown the possible presence of a stagnant region in the bottom of the tube that would influence the operation of the tube.

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