Heat Transfer in Evacuated Tubular Solar Collectors

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This paper outlines research on heat transfer in single ended all glass evacuated tubular solar collectors at The University of New South Wales.

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 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 splutter coaters for producing the absorber surface on all-glass evacuated tubes, Yin et al. (1987). Production of all-glass evacuated tubes in China is estimated to be more than 10,000,000 tubes/year in 2000. The majority of these tubes were used in domestic water heaters based on the water-in-glass design concept, which is the subject of this paper

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 continued 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 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 100mm diameter can function as both the absorber and the insulated hot water store. Tubes with 10 L to 20 L of storage have been developed.
- Evacuated tubes can also incorporate concentrating surfaces inside or outside the vacuum envelope.

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 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; 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.

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 and the 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 Figure 1.

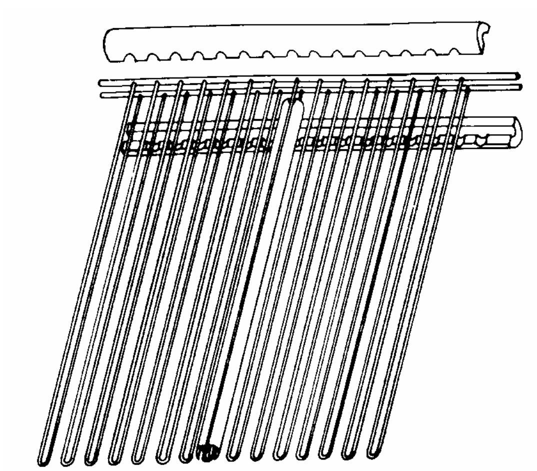

Figure 1. U-tube and heat removal fin used for pressurised all-glass evacuated tube solar collector.

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. Figure 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 inserted directly into a low pressure water tank as shown in Figure 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.

Figure 2. Water-in glass solar water heaters in China (Tsinghua Solar Beijing).

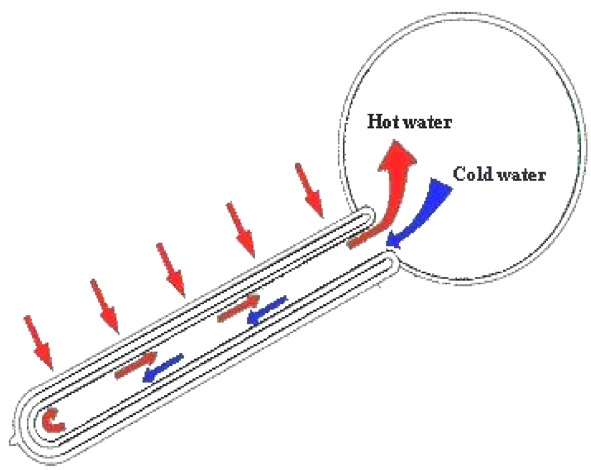

Figure 3. Cross-section of water-in-glass solar water heater.

Cylindrical Open Thermosyphon in Water in Glass Solar Collectors

A typical water-in-glass evacuated tube is shown in Fig 3. 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 splutter coaters for producing the absorber surface on all-glass evacuated tubes. Production of all-glass evacuated tubes in China is estimated to be more than 10,000,000 tubes in the year 2000.
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 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.

In order to investigate the flow structure and heat transfer within the tube, extensive experimental investigations have been done on cylindrical open thermosyphons with various tube aspect ratios, heating schemes and Rayleigh numbers. Extensive numerical modelling has been done for a number of years (Gaa et al., Behnia et al.)

Experimental Work

The experimental set-up shown in Fig 4 has been developed for the investigation of the flow inside an inclined cylindrical open thermosyphon [(6)]. A glass cylinder with a closed end at the bottom and an open end connected to a reservoir at the top is heated from the sides, generating a natural convection flow between the tube and the reservoir. The cylinder walls are heated in two different ways, uniform wall temperature 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.

Laser Doppler Anemometer (LDA) is used to measure the axial velocity at the central vertical plane of the orifice. The laser beam is directed by two mirrors on the way to the beam splitter then split into two beams of equal intensity at the splitter and then focused inside the thermosyphon tube. Reflected light, which contains the velocity information, is received by a photomultiplier, attached to the beam splitter assembly and converted to an electrical signal. These signals are filtered and processed by the input conditioner and frequency counter with final processing by an on-line computer, which computes the velocity at the measuring point. Correlations between the axial velocity and the parameters (Rayleigh number, aspect ratio and mode of heating) are performed.

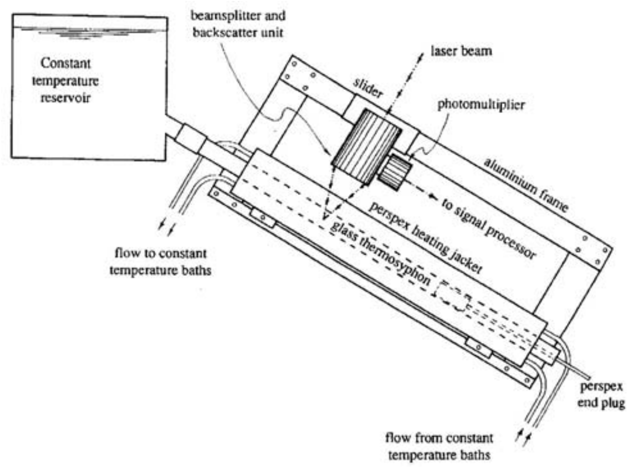

Figure 4: Experimental set-up to evaluate flow rates in single ended evacuated tube.

This work is an extension from the experiment previously reported by Behnia and Morrison on a similar experiment set-up [(7)]. They investigated the flow patterns inside the thermosyphon by means of a dye introduced through a nozzle and observed that a natural separation occurred between the inflow and outflow streams that was enhanced by the inclination of the cylinder. During steady-state uniform heating, a significant stagnant region was observed near the closed end of the tube. The existence of this inactive region would decrease the effectiveness of the heat transfer through the open end of the tube. It was also observed that in the uniform heating mode, there is a greater amount of mixing between the incoming cold stream and the outgoing warm stream due to warm currents being generated from all sides.

Numerical Work

A numerical model of the inclined open thermosyphon has been developed using a finite difference algorithm to solve the vorticity vector potential form of the Navier-Stokes equations [(2)]. The geometry considered was an open cylinder, inclined at 45° to the vertical, as shown in Fig 5. Steady flow is simulated at various combinations of Rayleigh number, aspect ratio and mode of heating. Two heating schemes were used, uniform wall heating and differential wall heating.

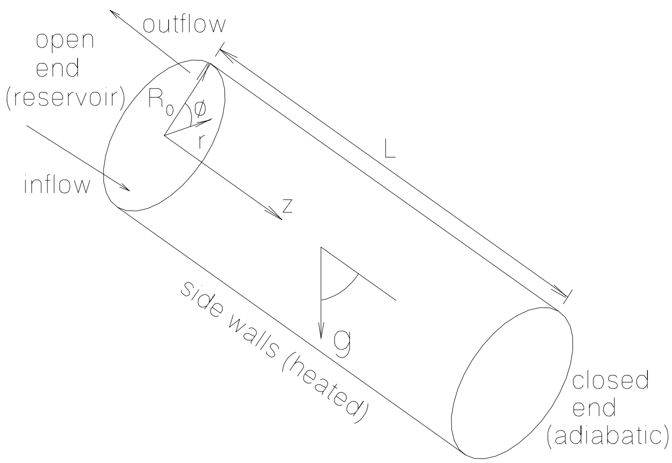

Figure 5. Computational domain

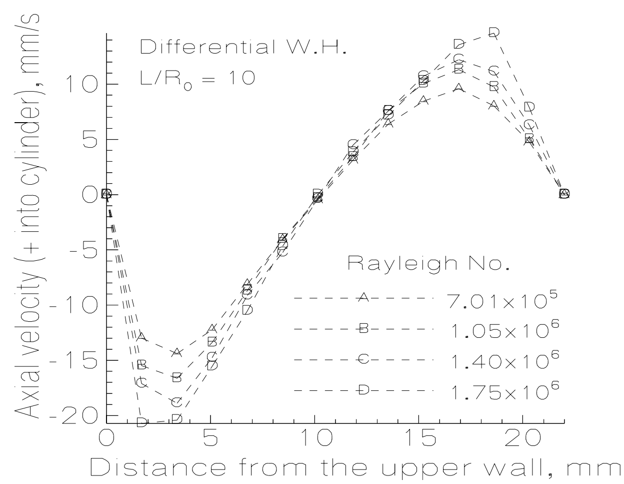

Fig 6. Measured axial velocity profiles at the orifice, differential wall heating, aspect ratio 10

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 as shown in Fig 6. 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).

Recent work includes numerical simulation of open thermosyphons with higher aspect ratios using FLUENT software. Uniform wall heating and differential wall heating were used as a validation of the simulation against the experimental results. In reality, tubes in a solar collector receive radiation directly from the sun, as well as from the reflectors underneath which results in variable heat flux around the absorber tube wall. 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 0 at the side. The effect of a constant heat flux boundary condition has also been investigated. Variations with aspect ratio and the Rayleigh number were investigated. So far, the modelling has been restricted to laminar flow, with Rayleigh number varying between 1000 and 10000.

A significant stagnant region was observed in tubes with uniform wall temperature with low Rayleigh number, as was in the experiment by Behnia and Morrison (see Fig 7). The flow is more stable when a heat flux boundary condition is applied on the sidewall. For tubes with large aspect ratio (L/r=80), a higher velocity was observed on the outgoing flow, with the hot flow leaving the tube through a smaller proportional area. The flow is still bi-filamental along the tube with relatively little degree of mixing. In reality, the condition on sidewall is somewhere between a heat flux and constant temperature boundary condition, so the effectiveness of the heat extraction from the tube still needs to be investigated further.

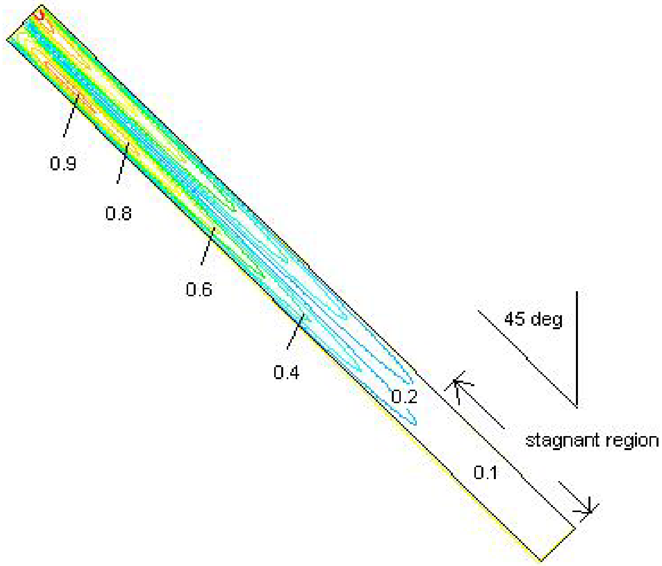

Figure 7. Numerical results showing stagnant region at the end, uniform wall heating.

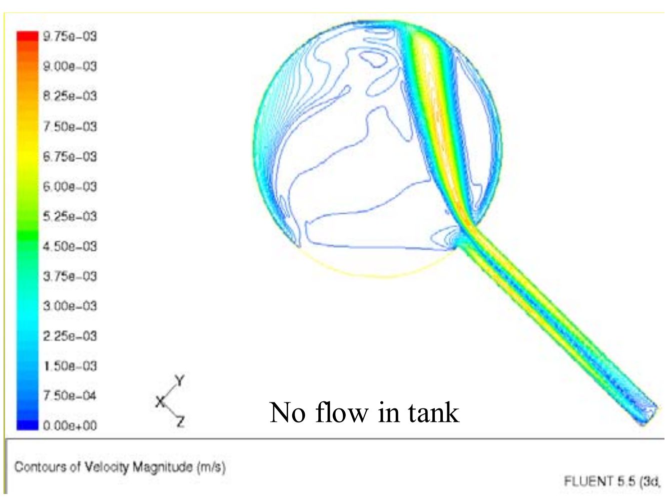

Fig 8. Flow structure between a single ended evacuated tube and a storage tank.

The interaction between an evacuated tube and a storage tank is being evaluated to determine the mass flow rate through the tubes. Preliminary results indicate that the flow rate through each tube for 1000 W/m2 solar radiation is of the order of 20 kg/hr. This would result in destratification of the storage tank. Factors influencing the mass flow rate are currently being investigated

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