DIURNAL REVERSE FLUID FLOW IN THERMOSYPHON EVACUATED TUBE SOLAR WATER HEATERS IN A NORTHERN MARITIME CLIMATE

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Abstract

Proprietary evacuated tube solar water heaters have superior thermal performance in Northern Maritime climates compared with proprietary flat plate solar water heaters. Typically delivering 5-15% more thermal energy per annum, this is, however, achieved with higher capital costs. The adoption of thermosyphon fluid circulation compared with forced circulation systems allows the capital cost of solar water heating systems to be reduced, reliability increased and similar levels of performance to be achieved, for well designed systems.

The thermal performance of an evacuated tube solar water heater system utilising thermosyphon fluid circulation subjected to Northern Maritime climatic conditions at the University of Ulster was monitored from the 23rd of September to 21st of November 2006. Measurements including collector outlet temperatures, mean bulk tank temperatures, ambient temperatures, and incident solar radiation levels were used to determine diurnal efficiency.

The manifold of an evacuated tube solar water heater was inclined at 1˚: the manifold outlet being higher than the inlet. During the monitoring period it appeared that thermosyphon flow did not always occur in the direction expected. It was deduced that flow reversal had occurred when the collector inlet temperature was greater than that of the outlet. Comparison of the calculated diurnal efficiency for the days when flow reversal occurred with those when it did not indicated that flow reversal reduced the mean calculated diurnal efficiency by approximately 13%.

Introduction

The combustion of fossil fuels generates carbon dioxide and other air pollutants, increasing their atmospheric concentration. It is predicted that the anthropogenic influence on the concentration of atmospheric carbon dioxide will increase mean global surface temperatures by 2.4°C to 5.4°C by the end of the 21st century, (Murphy et al, 2004). Solar thermal technologies can displace fossil fuels, reducing the emission of air pollutants. In Northern Maritime climates, evacuated tube and flat plate absorbers are integrated within solar water heating systems to generate thermal energy. Evacuated tube solar water heaters (ETSWH) have lower thermal losses and thus higher efficiency than flat plate solar water heaters (FPSWH), (Morrison et al., 1984). An evacuated, (10^{-5} bar), glass envelope reduces convective and conductive losses from the solar absorber to the ambient environment and solar selective coatings reduce radiative heat loss from the absorber. Heat-pipe ETSWHs utilise the excellent heat transfer properties of heat pipes to transfer solar energy to the circulation fluid. Heat-pipes can withstand freezing, have no moving parts, require no external pumping power and behave as thermal diodes. The rate of heat transfer from the absorber to the condenser is self-regulating as the evaporation/condensation processes within the heat pipe occur at a greater rate at higher insolations and at a lower rate at lower insolations. Figure 1 depicts a schematic diagram of a heat pipe ETSWH.

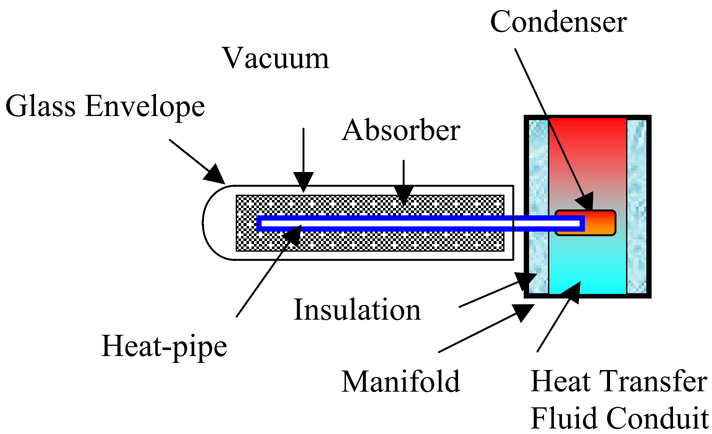

Fig. 1 Heat pipe ETSWH

ETSWHs have higher capital costs compared with either FPSWHs or fossil fuel systems. Solar water heaters utilising thermosyphon fluid circulation operate as effectively as pumped systems, but with lower initial and running costs, (Norton et al, 2001). An unfortunate characteristic of thermosyphon solar water heaters is the possibility of fluid flow reversal, induced when the mean Collector Fluid Temperature (CFT) is lower than the Mean Bulk Tank Temperature (MBTT), (Norton and Probert, 1983). This condition can arise frequently in Northern Maritime climates, as hot water storage tanks must be maintained at temperatures greater than 50°C to prevent the growth of *legionella pneumophila*, (DGS, 2005). Fluid flow reversal during daytime collection periods reduces the thermal efficiency of solar water heating systems by degrading the thermal stratification by convective entrainment. This flow reversal occurs due to the reduction in incident solar radiation associated with sunset or during cloudy conditions. This induces dissimilar rates of cooling within the system. Temperatures within pipe work external to the Hot Water Storage Tank (HWST) and collector eventually approximate ambient conditions whereas the collector and hot water storage tank cool more slowly due to their greater thermal mass and excellent insulation. Due to the number of variables affecting the value of MBTT and CFT at any particular moment, when thermosyphon solar water heating systems are operated in Northern Maritime climates, it is difficult to determine exactly why fluid flow reversal has occurred in any specific case, (Norton and Probert, 1983). The configuration of proprietary ETSWHs is such that, the occurrence of diurnal reversed fluid flow is more probable than in FPSWHs. This is explained with reference to figures 2 and 3. Figure 2 depicts a schematic diagram of a conventional open loop thermosyphon FPSWH. The configuration of solar water heating systems utilising evacuated tube solar water heaters differs from the configuration depicted in figure 2 as the inlet (Port A) and outlet (Port B) of the collector are both located at the same datum level as illustrated in Figure 3. If figure 2 is examined and, assuming all fluid temperatures being similar, then a greater hydrostatic pressure is exerted at Port A than at Port B, due to the height differential which exists between the fluid columns contained within the up-riser and down-comer. When solar radiation is incident on the collector, thermosyphon fluid flow occurs in the expected direction. If the situation depicted in figure 3 is considered and again assuming that temperature distributions within the fluid columns are similar, then an equal hydrostatic pressure is exerted at port A and port B.

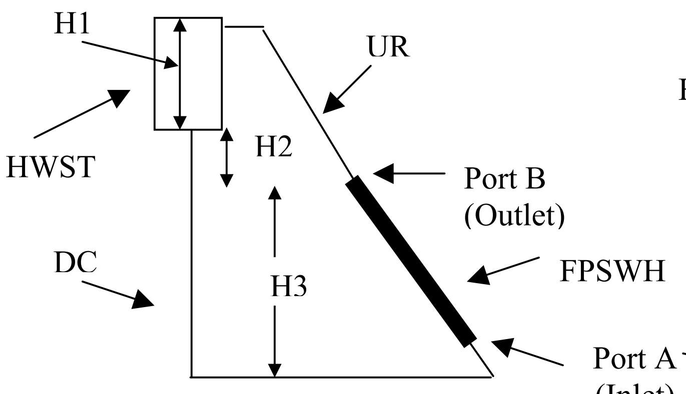

Fig. 2 Thermosyphon FPSWH

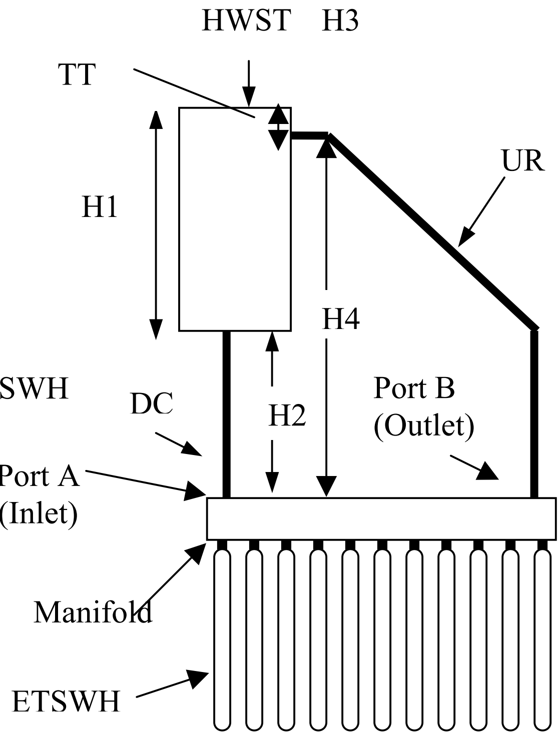

Fig.3 Thermosyphon ETSWH

Whenever solar radiation is incident on the collector array, thermosyphon fluid flow could, theoretically occur in either direction. The fluid column within the up-riser contains a greater proportion of external pipe work and has less thermal mass than the combined fluid column of the hot water storage tank with down-comer (HWST/DC), and thus cools more rapidly. In Northern Maritime climates, situations where the fluid column contained within the up-riser/top section of hot water storage tank (UR/TT) is at a lower temperature than the fluid column contained with the HWST/DC will be encountered frequently in practice. In this case the thermosyphon fluid flow direction would be reversed. Thermosyphon fluid flow is driven by buoyancy forces induced via heat transfer. The fluid circulating within the collector loop gains momentum due to buoyancy forces so the initial fluid flow direction is maintained. Figure 3 demonstrates how the buoyancy stimulating temperature differential (BSTD) inducing fluid motion within a thermosyphon solar water heater may be calculated by subtracting the mean temperature of HWST/DC from the mean temperature of the UR/TT, (Norton and Probert, 1983). A negative value of BSTD indicates fluid flow reversal. This relationship assumes a linear temperature distribution throughout the system, and uniform insulation of all pipe work. For the system depicted in figure 3, equations 1 and 2 are used to determine the mean temperature of the fluid columns.

$$\overline{T}_{DCHT} = \frac{\overline{T}_{DC} H_2 + \overline{T}_{HT} H_1}{H_2 + H_1} \qquad (1)$$

$$\overline{T}_{URTT} = \frac{\overline{T}_{UR} H_4 + \overline{T}_{TT} H_3}{H_4 + H_3} \qquad (2)$$

The BSTD driving the thermosyphon fluid flow is calculated from equation 3.

$$\Delta_{BSTD} = \overline{T}_{URTT} - \overline{T}_{DCHT} \qquad (3)$$

Methodologies to reduce or prevent the occurrence of thermosyphon fluid flow reversal can be divided into passive and active modifications. Active modifications for preventing reverse fluid flow incorporate one-way valves within the collector loop to ensure that fluid flow occurs in the expected direction. Unfortunately one-way valves lead to increased frictional losses and durability may be an issue, (Norton and Probert, 1986). Passive methods for the prevention and reduction of reversed fluid flow utilise modified system geometries. Norton and Probert (1983) suggested locating the hot water storage tank above the collector outlet; the magnitude of the separation was dependent on the temperature distributions within the system in question at any one particular moment considered. Morrison (1986) measured the magnitude of heat loss induced via nocturnal reverse fluid flow, from a FPSWH exposed to the climatic conditions of Sydney, Australia. The hot water tank was located 250mm above the collector outlet; measured heat loss was less than 0.5MJ/day, (Morrison, 1986). Prapas and Sotiropoulos (1991) proposed enclosure of the up-riser within the hot water storage tank. When incident solar radiation levels were reduced its temperature cooled more slowly relative to the down-comer. This modification however reduced thermal efficiency as inlet temperatures increased and the temperature differentials driving thermosyphon fluid flow were reduced.

Redpath et al. (2006) investigated thermosyphon fluid flow regimes by undertaking experiments with a truncated, 5-pin fin acrylic model of the manifold of a heat pipe ETSWH. Thermal energy was supplied via electric heaters. Fluid flow reversal occurred when the manifold was orientated horizontally. This study proposed inclination of the acrylic manifold so that Port B was located at a higher level than Port A, inducing a hydrostatic pressure differential. This ensured fluid flow occurred in the expected direction. As the inclination of the acrylic manifold was increased from the horizontal, buoyancy forces had an increased effect on the enclosed fluid. Fluid flow reversal was prevented under these conditions at manifold inclination angles equal to or greater than 1°. This study was only undertaken for a laboratory model under steady conditions and results were not validated by data gathered from operational thermosyphon ETSWHs. Inclination of ETSWH manifolds is a simple passive modification intended to reduce or prevent reversed fluid flow during diurnal collection periods.

Experimental Technique

Data on the thermal performance of ETSWHs was gathered from monitoring a heat pipe ETSWH, (area 2m^2) for 44 days. The ETSWH array comprised 20 evacuated tubes and was connected to a hot water storage tank of 245 litres capacity. Incident solar radiation was recorded using a proprietary pyranometer to an accuracy of ±3%. Temperature measurements were made at Port A, Port B, tank inlet, tank outlet and the ambient using platinum resistance devices located within thermal pockets, to an accuracy of ± 0.1°C. The MBTT was measured using an array of 7 T-type thermocouples evenly distributed along the central vertical axis of the hot water storage tank with an accuracy of ± 0.25°C. The output from these sensors were sampled every 10 seconds, averaged and then recorded every 5 minutes using a multi-channel logger. The thermal behaviour of the ETSWH was monitored from 0700 to 1900 (GMT) daily. After each diurnal period the system was drained and then replenished with water from the mains. The ETSWH was inclined at 1° from the horizontal the manifold outlet being higher than the inlet to determine whether this would prevent the occurrence of reverse circulation under Northern Maritime climatic conditions. The energy stored by the system was determined from the diurnal change in MBTT from 0700-1900 and was calculated using equation 4.

$$Q_{kWh} = C_p * V \ * \left(\overline{MBTT}_f - \overline{MBTT}_i \right) \qquad (4)$$

Results

The expected collector inlet was denoted as port A and the expected collector outlet denoted as port B. For 8 days of the tests the ETSWH had zero efficiency in terms of solar energy stored so these days were not included in the analysis. On 25 days fluid flow direction was reversed and on 11 days fluid flow occurred in the expected direction. It was deduced that flow reversal had occurred when the temperature of the collector inlet was greater than that of the collector outlet. From the diurnal periods considered, the efficiency of the system in collecting and storing incident solar radiation was calculated using equation 4 for fluid flows in each of the flow directions, as depicted in table 1.

Table 1 Diurnal Storage Efficiencies

Scenario (Flow direction)	Mean efficiency
ETSWH (mean)	47%
ETSWH (expected)	56%
ETSWH (reversed)	43%

From table 1, the mean diurnal storage efficiency of the ETSWH was calculated as 47%. When fluid flow direction was reversed, diurnal storage efficiency decreased by 13% compared with diurnal periods when flow was in the expected direction. Figure 4 depicts the hourly temperatures of Ports A and B alongside ambient temperature and incident solar radiation, calculated from averaged 5-minute data, for the ETSWH on the 23rd of October when fluid flow occurred in the expected direction. Figure 5 depicts the same parameters for the 2nd November when the fluid flow direction was reversed. Incident solar radiation levels on the 23rd October and the 2nd November were measured as 4.3kWh/m^2/day. Figure 6 depicts the variation in BSTD calculated using equations 1, 2 and 3, for the 23rd October and the 2nd November.

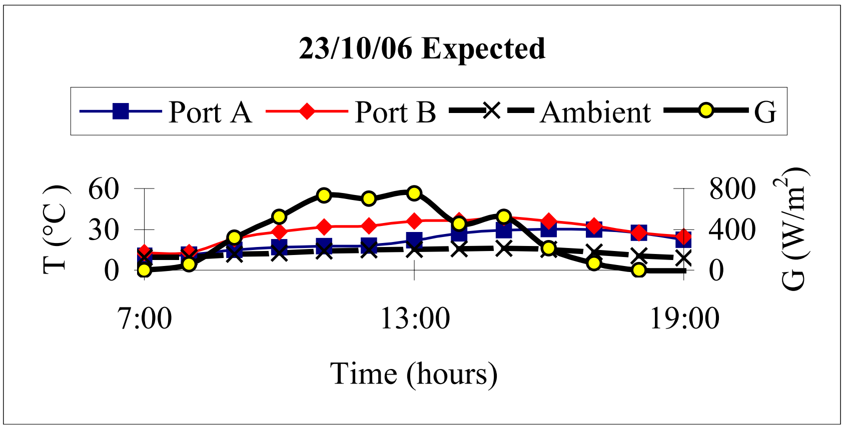

Fig. 4 Expected flow direction

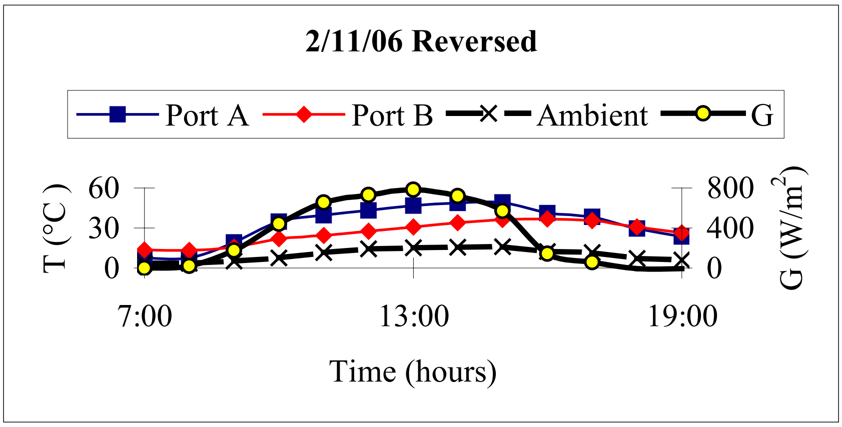

Fig.5 Reversed flow direction

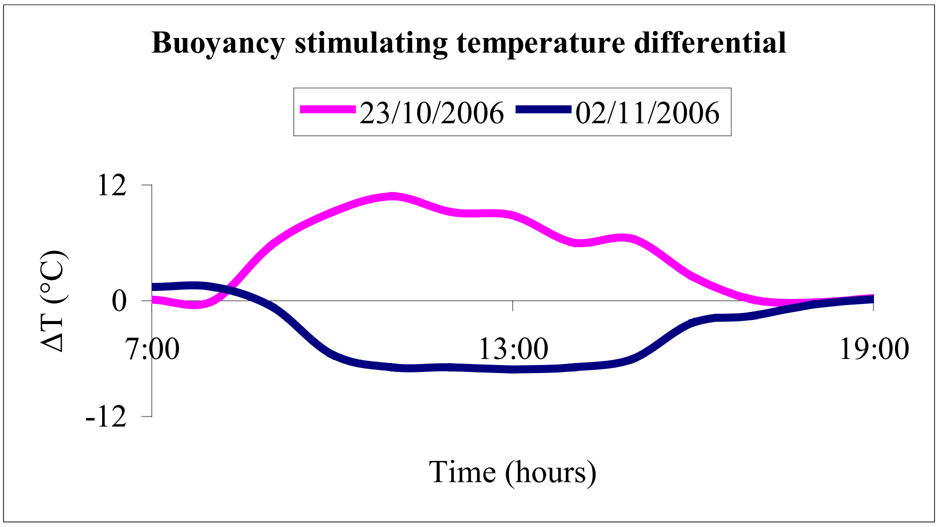

Fig. 6 BSTD

Analysis

From figure 5 on the 2nd November the calculated values for BSTD during the diurnal collection period were negative, corroborating the results presented in figure 6 that indicated fluid flow reversal. As depicted in figure 6, on the 2nd November the BSTD was negative and reduced in magnitude compared with the calculated BSTD for the 23rd October. The mean BSTD between 1200 to1300 on the 23rd October and 2nd November was calculated as 9°C and –7°C respectively. As depicted in figures 4 and 5, during this time period, hourly averaged incident solar radiation levels and ambient temperatures varied no more than 4% and 1% respectively. The measured CFT on the 2nd November from 1200 to 1300 was 27% greater than the value recorded for the same time period on the 23rd October. The thermal losses from the collector to the external environment on the 23rd October and 2nd November were 78W and 142W respectively when calculated using equation 5.

$$Q = kA\left(\Delta T / x\right) \tag{5}$$

The diurnal storage efficiency for the 23rd October and 2nd November 2006 was calculated using equation 4 as 54% and 41% respectively.

Conclusions

From the presented results, diurnal reverse circulation induced a significant heat transfer penalty compared with diurnal periods when thermosyphon fluid flow occurred in the expected direction. Diurnal efficiency of solar energy collection and storage were reduced by 13% when the thermal behaviour of the system from two diurnal periods with similar operating conditions were compared. The experimental observations of fluid flow reversal were supported by the relationship proposed by Norton and Probert (1983). System configurations that prevent diurnal reversed fluid flow should be developed so that the thermal performance of thermosyphon ETSWHs in Northern Maritime climates can be optimised.

Acknowledgments

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Abbreviations

BSTD Buoyancy stimulating temperature differential
CFT-Collector fluid temperature
DC-Down-comer
ETSWH- Evacuated tube solar water heater
FPSWH- Flat plate solar water heater
HWST- Hot water storage tank
MBTT- Mean bulk tank temperature

TT- Top of hot water storage tank
UR- Up-riser

Nomenclature

A-Area (m^2)
C_p- specific heat capacity (KJ/kg)
k-thermal conductivity (W/mK)
H-height (m)
Q-heat flux (W)
T-Temperature (°C)
V-volume (m^3)
x-thickness (m)

Greek Nomenclature

Δ-Difference

SUBSCRIPTS
$_f$-Final
i-Initial

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