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Investigation of the parameters affecting the thermosiphonic phenomenon in solar water heaters

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Abstract: Cyprus is currently the leading country in the world with respect to the application of solar water heaters for domestic applications, with more than 93% of the houses equipped with such a system. The great majority of these solar water heaters are of the thermosiphonic type. Thermosiphonic is a natural phenomenon where the flow of the solar heated water from the collector to the storage tank occurs from a small flow created due to the difference in density between hot and cold water. The main advantage of such systems is that they do not require a pump for circulating the water and circulation exists as long as there is sunshine. This reduces the maintenance requirements and the system is foolproof. In spite of the fact that extensive analyses of the performance of solar water heaters has been carried out by numerous researchers, almost all of them concerned forced circulation systems which use a circulating pump.

Currently, the knowledge on the parameters affecting the 'thermosiphonic phenomenon' is rather poor while on an international level (ISO and CEN committees) there isn't any standard to test thermosiphon solar collectors. The deeper understanding of the 'thermosiphonic phenomenon' and the identification of the key parameters affecting it, is the main aim of a research project currently in process in Cyprus.

In this work the first preliminary results of the experimental procedure are presented. More specifically, a special test rig was set up and equipped with all sensors necessary to measure all parameters that are most likely to affect the 'thermosiphonic phenomenon'. All tests were conducted according to ISO 9459-2:1995(E). The system was able to operate in various weather and operating conditions and could accommodate the change of inclination of the collector. Initially, the solar collector was tested according to EN12975-2:2006 in order to determine the thermal performance at a flow and operation conditions specified by the standard. Subsequently, the efficiency of the collector operating thermosiphonically was calculated based on quasi-dynamic approach. Finally, a series of correlations were attempted using the data acquired when the collector is operating themosiphonically which are the following: (i) the temperature difference of the water at the outlet and the inlet of the collector (ΔT) with the solar global radiation, (ii) the water mass flow with the solar global radiation, (iii) the water mass flow with the temperature difference of the water at the outlet and the inlet of the collector (ΔT). The results of the data analysis showed that these parameters are very well correlated between them since the coefficient of determination (R^2) is over 0.91 in all cases.

Keywords: *Thermosiphonic phenomenon, solar water heaters, Cyprus.*

1. INTRODUCTION

Cyprus has no natural oil resources at the moment and relies entirely on imported fuel for its energy demands. The only natural energy resource available is solar energy. Cyprus has a very sunny climate with an average annual solar radiation on a horizontal surface of 5.4 kWh/m^2-day.

Solar water heating units are extensively employed in Cyprus. In fact the total number of units installed, are such that constitute Cyprus to be the leading country in the world in this area. These units are mostly of the thermosiphonic type. This type of solar water heater consists of two flat-plate solar collectors having an absorber area between 3 to 4 m^2, a storage tank with capacity of 150 to 180 litters and a cold water storage tank, all installed on a suitable frame. An auxiliary electric immersion heater and/or a heat exchanger, for central heating assisted hot water production, are used in winter during periods of low solar insolation.

Because the manufacturing of solar water heaters and mainly that of the thermosiphon type has expanded rapidly in Cyprus, there is a need to study in depth and model this type of systems. It is also required to validate the model using simple physical experiments. In this way the model can be used to investigate the effect of design changes and therefore improve the solar water heater performance.

2. LITERATURE REVIEW

There have been extensive analyses of the modelling, analysis and performance of thermosiphon solar water heaters, both experimentally and analytically by numerous researchers (Kalogirou, 2009). Some of the most important are shown here.

Close (1962) made the first published analysis of thermosiphon solar water heater circuit. He has presented a mathematical model where mean system temperature and water mass flow rate can be predicted by testing two thermosiphon systems with different characteristics. The results conformed well to those predicted.

Desa (1964) considered the water heater system on the whole and by equating the incident energy received to the sum of the heat losses from it and the heat gained by the water, predicted the mean water temperature variation throughout the day for a natural circulation flow system.

Gupta and Garg (1968) modified the model of Close (1962) to take into account the heat exchange efficiency of the collector absorber plate and thermal capacitance. They have improved Close's analysis by incorporating a plate efficiency factor to account for the thermal efficiency of the plate and approximating ambient conditions using Fourier's series expansions for ambient temperature and radiation intensity. So they developed a model for thermal performance of a natural circulation solar water heater with no load and presented solar radiation and temperature with Fourier series. They also found experimentally that the flow rate of a thermosiphon water heater can be increased by increasing the relative height between the collector and storage tank, but the efficiency is not increased. The efficiency can be increased by reducing the loop resistance.

Ong (1974, 1976) evaluated the thermal performance of a thermosiphon solar water heater. He used a small system with five thermocouples on the bottom surface of the water tubes and six thermocouples on the bottom surface of the collector plate. The six thermocouples were inserted into the storage tank and a dye tracer mass flow meter was employed. His studies were the first detailed ones on a thermosiphonic system. Ong (1974) extended the work of Close (1962) and Gupta and Garg (1968) as he presented a finite difference method of solution to predict the mean system temperature and water mass flow rate in a solar water heater operating under thermosiphon flow conditions. The experimental results presented, showed that the mean collector plate temperature, the average water temperature in the storage tank and the mean water temperature in the collector tubes were not equal. Furthermore, the tank temperature distribution was non-linear. All these were contrary to the theoretical assumptions that the mean temperatures were equal corresponding to a single mean system temperature and that the tank temperature distribution was linear. In 1976 he wanted to improve the theoretical assumptions made previously in 1974, in order to obtain a more satisfactory agreement between experimental data and prediction. Therefore, in 1976, an improved theoretical model was presented to predict the thermal performance of a natural-recirculation solar water heater system.

Morrison and Ranatunga (1980) investigated the response of thermosiphon systems to step changes in solar radiation. Measurement of the transient flow rate was obtained using a laser Doppler anemometer and a mathematical model was developed to simulate the transient performance. Results shown that although there are long time delays associated with the development of the thermosiphon flow the energy collection capability is not affected by thermosiphon time delays.

Morrison and Sapsford (1983) investigated the performance of 6 thermosiphon solar water heaters while they were supplying typical domestic hot water loads. The performance of the solar systems was rated by comparing the auxiliary energy consumption with the energy consumed by a conventional electric system. In contrast to forced circulation systems the performance of thermosiphon systems was found to be best if a morning peak load pattern was used. Their results showed that the performance of thermosiphon solar water heaters is a function of the way the system is operated and that significant variations of performance exist between different systems configurations.

The results from the two previous studies have been used by Morrison and Tran (1984) to develop a simulation program for thermosiphon solar water heaters supplying various domestic energy demand patterns. Morrison and Tran (1984) presented a finite element simulation model for prediction the long term performance of thermosiphon solar water heaters. The simulation results indicate that the performance of a solar water heater with an in-tank booster improves as the flow rate through the collector is reduced. Also found that the efficiency of a thermosiphon system with in-tank booster is slightly higher than an equivalent pumped circulation system, due to better stratification in the storage tank in the thermosiphon system.

Kalogirou and Papamarkou (2000) studied the modelling of a thermosiphon solar water heating system and carried out a simple model validation in Nicosia, Cyprus. They used two flat plate collectors with an area 2.7 m^2 and a storage tank of 150 l modelled using TRNSYS so to have a detailed analysis and a long term system performance. They found that the annual solar contribution of the simulated system was 79% and during the summer months no auxiliary heating is required as the solar contribution of the simulated system was 100%. However, during the summer months the demand for hot water from storage tank was reduced. Experimentally they found that there is a decrease in solar radiation during May because of special conditions to the development of clouds encountered in Nicosia. They also made an economic analysis, which they found that the payback time of the system is 8 years and the present worth of life cycle savings is equal to 161 Cy pounds (€275).

Runsheng *et al.* (2010) studied a thermosiphon domestic solar water heater with flat plate collectors at clear night and found that thermosiphon domestic solar water heater flat plate collectors with a non solar selective absorber might suffer from freezing damage.

Sakhrieh and Al-Ghandoor (2012) made an experimental investigation of overall performance, efficiency and reliability of five types of solar collectors as used in the Jordanian market. The five types that they studied are blue coated, black coated, cooper, aluminium and with evacuated tubes. They observed that the outlet temperature (T_{out}) of the five types increases during the day and reaches the peak at about 2 o'clock p.m. and then starts to decrease. The efficiency curve against time has the same shape as the T_{out} curve. They concluded that evacuated tube solar collector has the highest efficiency followed by black and blue coated solar collectors. The aluminium collector comes in the fourth place as the lowest efficiency is reserved for the copper collector.

As can be understood from this literature review although many scientists have carried out research on various aspects of the thermosiphon system, nobody was concerned with the ability of the system to generate the thermosiphon loop which is the main objective of this project. This will show how the performance of such systems can be improved as there is a good possibility that not all flat-plate collectors are suitable to be used in thermosiphon solar water heating systems, as it is done today, without too much consideration on the actual performance of the system. In this work, the first preliminary results of the experimental procedure are analysed in order to find out the correlations between some of the main parameters such as the solar global radiation, the temperature difference of the water on the outlet and the inlet of the collector and the water mass flow.

3. DESCRIPTION OF THE TEST RIG

The thermosiphon test rig used for the experimental procedure, shown in Figure 1, was assembled by the staff of Applied Energy Laboratory of the Cyprus Ministry of Commerce, Industry and Tourism and consists of three main components namely the Test Rig, the Cylinder and the Heat Sink which are described below.

Test Rig: The Test Rig is made out of galvanized steel and it was designed to adjust the angle of collector. For the adjustment of the angle of the collector, a fully automatic pneumatic stroke is installed. The angle of the collector is measured with an inclinometer. In addition, the Test Rig is designed so that the height between the collector and the Cylinder can be adjusted. Additionally, a pyranometer is attached on the Test Rig, in order to measure the global radiation during the test period.

Cylinder: The Cylinder is made out of copper and it is insulated with natural mineral wool. Sensors are attached on the cylinder, for recording the temperature of the water such as:

1. Inlet Temperature (2 x PT100)
2. Outlet Temperature (2 x PT100)
3. Draw off inlet and outlet (2 x PT100)
4. Mixing temperature (2 x PT100)
5. Stratification temperature (5 x Thermocouple)
6. Inlet and Outlet of the Heat Exchanger (2 x PT100)

A pneumatic ball valve is attached at the draw off outlet in order to regulate the flow at the draw off period. In addition, a mixing pump is attached at the back of the cylinder. Furthermore, the cylinder is equipped with a magnetic flow meter for measuring the flow at the exit of the collector, and a second portable ultrasonic flow meter is attached at the inlet pipe of the collector. It has also a differential pressure transmitter for measuring the pressure drop of the collector.

Heat Sink: A supply tank is used as heat sink, which provides water to the system. At the exit of the supply tank, there is a three-way valve with an actuator, and a pump. This allows regulating the temperature and flow of the water which is provided to the system.

Figure 1 Front view of the test rig

3. METHODOLOGY

The data analysed in this paper were recorded using Agilent data acquisition equipment between the 29th of May and the 13th of June. The data were recorded from 07:30 to 18:45. The area of the collector used for the experiments was 1.36m^2, its orientation was south and its inclination angle was constant at 45°, which is the angle used by most solar water heating systems in Cyprus.

Initially, the solar collector was tested according to EN12975-2:2006 in order to determine the thermal performance at a flow and operation conditions specified by the standard. According to the standard, the experimental parameters needed to compute the collector's efficiency under constant inlet temperature and mass flow during a test period, are the water temperature at the collector inlet, water temperature at the collector outlet, water mass flow, solar global radiation, ambient temperature and wind speed. Subsequently, the test was repeated with the collector operating thermosiphonically.

Finally, several correlations were attempted which are the following:

(i) the temperature difference of the water at the outlet and the inlet of the collector (ΔT) with the solar global radiation,

(ii) the water mass flow with the solar global radiation,

(iii) the water mass flow with the temperature difference of the water at the outlet and the inlet of the collector (ΔT).

All tests were conducted according to ISO 9459-2:1995(E).

4. RESULTS AND DISCUSSION

The results concerning the thermal performance of the collector according to EN12975 and under thermosiphonic operation are depicted in Figure 2. It can be observed that the thermal performance according to EN12975 is slightly higher than that of the thermosiphonic operation, which is rather logical due to the fact that the flow during the thermosiphonic operation is lower than the one according to EN12975 since it is naturally created as a result of the temperature difference between the inlet and the outlet water of the collector (thermosiphonic phenomenon). The equation of the performance of the collector according to EN12975 is:

$$\eta = 0.7025 - 4.3377\frac{T_m - T_a}{G} - 0.1630\frac{(T_m - T_a)^2}{G} \quad (1)$$

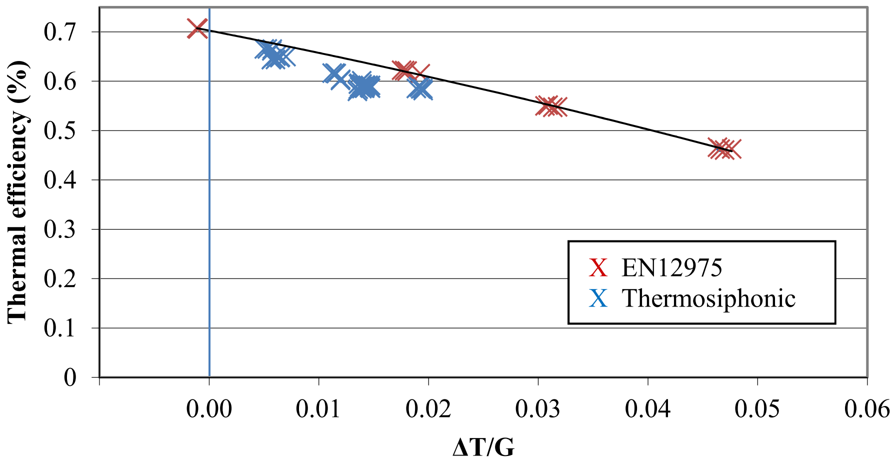

Figure 2 Efficiency of the solar collector according to EN12975 and under thermosiphonic operation

The results correlating the solar global radiation (G) with the temperature difference between the water inlet and outlet of the collector (ΔT) are depicted in Figure 3 where, as can be observed, they are very well correlated since the coefficient of determination (R^2) is 0.9571. This result is rather logical since when the incident solar radiation, being the motive power of the thermosiphonic phenomenon, is higher, the temperature difference between the water inlet and outlet also increases. The equation describing the relation between them is the following:

$$\Delta T = -1.02\times10^{-5}(G)^2 + 0.02579(G) - 1.63097 \quad (2)$$

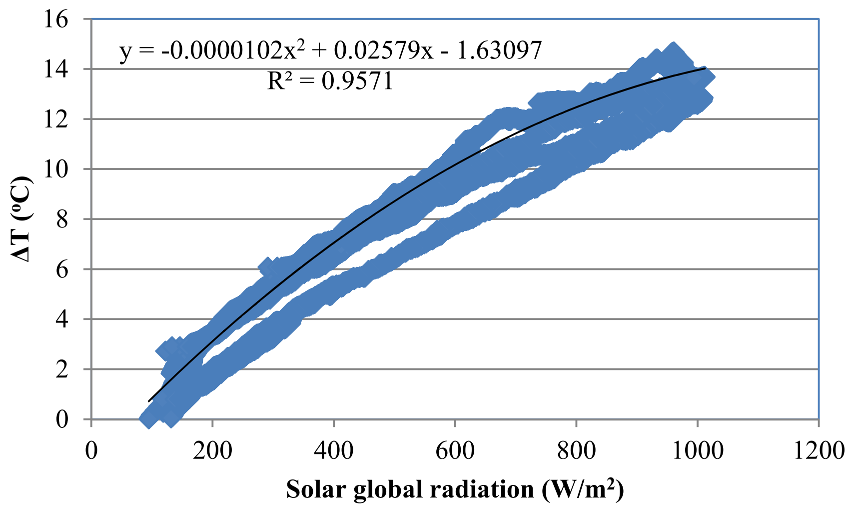

Figure 3 Correlation of the solar global radiation to the temperature difference of the water in and out of the collector

As can be seen from Figure 3, quite substantial temperature differences of the order of 15°C are developed in the collector, because of the action of solar radiation. The higher values, as expected, occur at the higher radiation input. It should be noted that by heat rejection the temperature in the storage tank was kept constant (to within 5-6°C) throughout the day.

The results correlating the solar global radiation (G) with the water mass flow (m) are presented in Figure 4. It can be observed that they are also very well correlated since the coefficient of determination (R^2) is 0.9698. From this result it can be concluded that this water mass flow which is naturally created from the temperature difference of the water at the outlet and the inlet of the collector (thermosiphon phenomenon) is directly correlated to the amount of the incident solar radiation on the collector. The equation describing the relation between them is the following:

$$m = -5.6x10^{-8}(G)^2 + 0.00001830(G) + 0.00085838 \quad (3)$$

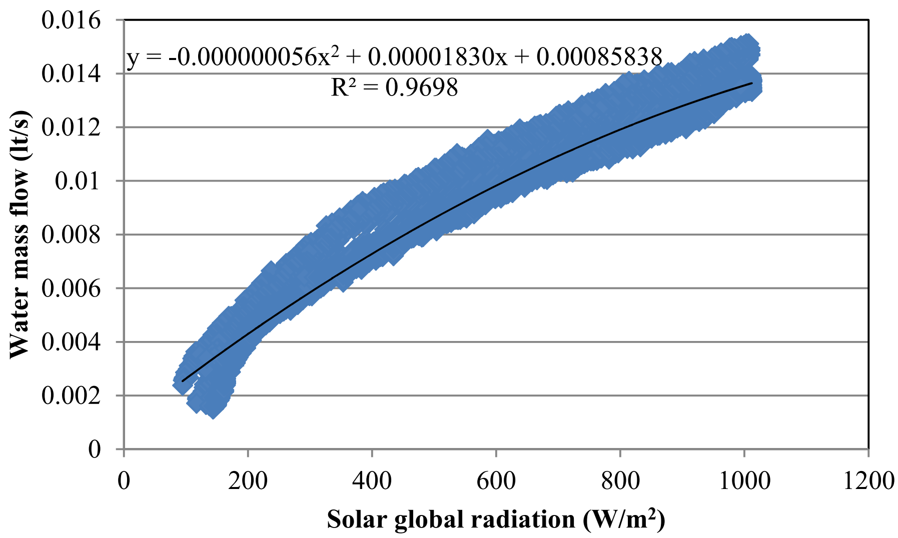

Figure 4 Correlation of the solar global radiation to the water mass flow

As can be seen from Figure 4 a flow rate of about 0.015 lt/s is created by the thermosiphonic effect at the higher radiation levels. By using the collector area of 1.36m^2, this gives a value of 0.011 lt/s/m^2, which is about half the flow rate specified by EN 12975 for testing the solar collectors (0.02 lt/s/m^2). This explains the slightly lower performance of the collector operating thermosiphonically shown in Figure 2.

The results correlating water mass flow with the temperature difference between the inlet and the outlet water of the collector are depicted in Figure 5. As can be observed they are also very well correlated since the coefficient of determination (R^2) is 0.9167. The equation describing the relation between them is the following:

$$m = 3.7x10^{-6}(\Delta T)^2 + 0.00096(\Delta T) + 0.0018962 \quad (4)$$

As expected the higher temperature differences create higher flow rates and vice versa. Both values depend on the input power, which is the solar radiation, so the higher values correspond to the higher values of solar radiation input on the collector.

5. CONCLUSIONS

This work constitutes the first preliminary data of a research project currently in process in Cyprus, which aims to gain deeper understanding of the 'thermosiphonic phenomenon' and the identification of the key parameters affecting it.

Specifically, a special test rig was set up and equipped with all sensors necessary to measure all parameters that are most likely to affect the 'thermosiphonic phenomenon'. All tests were conducted according to ISO 9459-2:1995(E). The system was able to operate in various weather and operating conditions and could accommodate the change of inclination of the collector. Initially, the solar collector was tested according to EN12975-2:2006 in order to determine the thermal performance at a flow and operation conditions specified by the standard. Subsequently, the efficiency of the collector operating thermosiphonically was calculated based on quasi-dynamic approach.

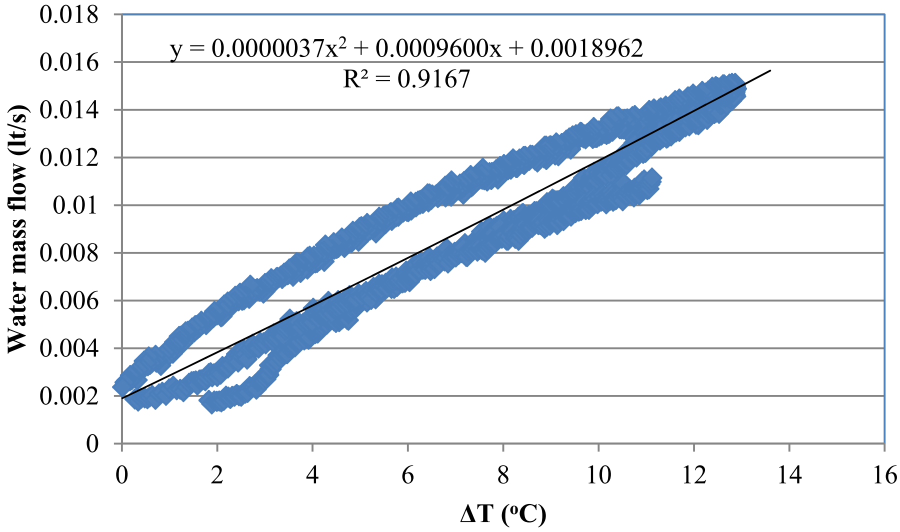

Figure 5 Correlation of the water mass flow to the temperature difference of the water in and out of the collector

Finally, a series of correlations were attempted using the preliminary data acquired when the collector is operating thermosiphonically for the temperature difference of the water at the outlet and the inlet of the collector, the solar global radiation and the water mass flow.

The results of the data analysis showed that these parameters are very well correlated between them since the coefficient of determination (R^2) is over 0.91 in all cases. These results are very interesting since they give initial inside information of the relation between some of the main parameters that are most likely to affect the thermosiphonic phenomenon. The work is ongoing and the objective is also to find how the collector inclination and the distance between the top of the collector and the bottom of the storage tank affect the performance of the system. This work will lead to the suggestion of a new test procedure suitable for thermosiphonic units.

6. ACKNOWLEDGMENTS

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