A Review of Experimental Studies on Traditional Thermosyphon Solar Water Heaters

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ABSTRACT

The Thermosyphon Solar Water Heater (TSWH) is the most widely used of all man-made solar thermal devices. However, the physical phenomena underlying its mode of operation are complex and some of the published experimental results appear to be contradictory.

This review paper is an attempt to present the available basic information on TSWH performance in a systematic manner. Various criteria of performance, test methods and typical experimental results are discussed. Parameters such as relative height of storage tank, ratio of storage tank volume to collector aperture area and pipe insulation, and their effects on the dynamics of solar thermosyphon systems are also discussed. The paper concludes by identifying some of the areas which need further investigation.

INTRODUCTION

The Thermosyphon Solar Water Heater (TSWH) is the most widely used of all man-made solar energy conversion devices [1]. By 1978, 30% of the Israeli population utilised TSWH systems and today there are more than 60,000 units operating in Israel [1,2]. It is estimated that 10% of all households in Japan have solar water heaters on the roof-top [3]. TSWH systems are also widely used in Australia and they are manufactured commercially in Greece and the United States [4].

TSWH systems are not popular in the developing countries, particularly those which lie in the tropics. The reasons are both socio-economic and technical. First, hot water for domestic use is of little or no importance to the majority of people, most of whom live in rural areas and have more vital needs than a hot bath in the morning. Other reasons include the high initial cost and the relatively low temperatures delivered by TSWH systems.

There are several types of TSWH systems. Some employ special heat transfer fluids with heat exchangers and others incorporate an electric booster (auxiliary heater) in the storage. An extensive review of these systems has been undertaken by Norton and Probert (1982)[5] and by Mertol and Grief (1985)[6,7].

TSWH systems have attracted the attention of many researchers throughout the world and in sub-Saharan Africa in particular, where experimental models and demonstration prototypes can be seen at University campuses and research institutes [8]. This attraction derives from the fact that a TSWH system does not require auxiliary energy for circulating the heat transfer fluid. However, the physical phenomena underlying its mode of operation are complex and some of the published experimental results appear to be contradictory.

This review paper is an attempt to present the available basic information on TSWH systems in a systematic manner. The main objective is to seek an understanding of the dynamics of solar thermosyphon systems. We concentrate on the traditional solar thermosyphon system which uses ordinary water as the heat transfer fluid and has no auxiliary heater. We also limit attention to cases without draw-off or make-up water, at least during periods of energy collection. Emphasis is placed on experimental measurements while analytical studies and computer simulations are referred to inasmuch as they help to clarify the underlying principles of TSWH systems.

SOLAR THERMOSYPHON SYSTEM

Figure 1 presents a schematic diagram showing the main components of a traditional solar thermosyphon hot water system. Heat is transferred from the collector plate to water in the riser

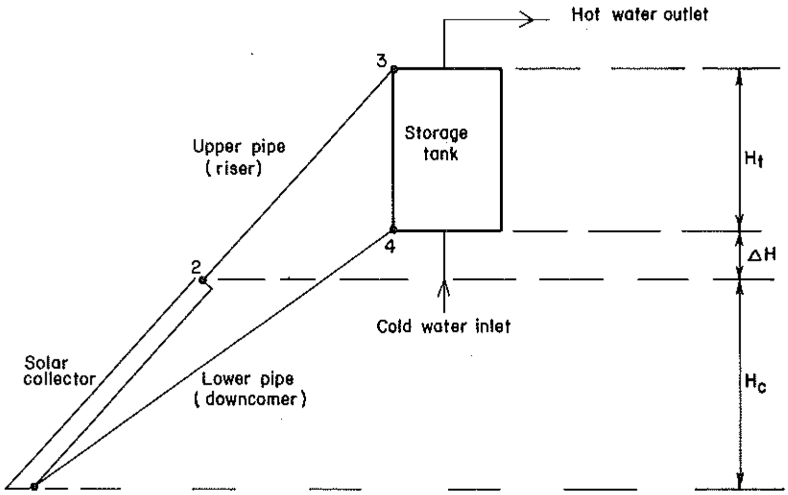

Fig. 1(a). Schematic diagram of a solar thermosyphon hot water system.

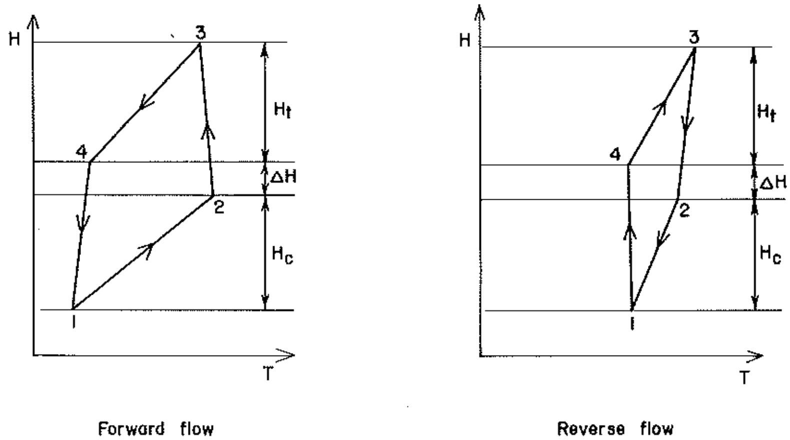

Fig. 1(b). Height-temperature profiles in a solar thermosyphon hot water system.

tubes in thermal contact with the plate. The temperature of water in the collector rises and the density decreases, relative to other parts of the loop, resulting in unbalanced gravitational body forces which cause fluid motion into the storage tank. Since water is nearly incompressible, and continuity is ensured, all parts of the loop also move. Hot water rises to the top of the storage tank while cold (or less hot) water flows from the bottom of the tank into the collector. Thus, a circulation is maintained as long as energy is absorbed in the solar collector.

Figure 1 also presents the general form of the height-temperature profile in the system. The thermosyphon head, which is responsible for the flow in the system, is equivalent to the area enclosed by the height-temperature curve. Area is considered positive if enclosed by an anti-clockwise profile and a positive area is associated with forward flow while a negative area goes with reverse flow.

Thus, knowledge of the instantaneous system temperature distribution is most essential in the evaluation of the thermosyphon head which is the driving force at the heart of the solar thermosyphon hot water system. The thermosyphon head acts in opposition to the loop resistance, which is a combination of wall friction and losses through bends, constrictions, etc. Under steady state conditions (i.e. constant mass flowrate and constant collector inlet and outlet temperatures), the thermosyphon head would equal loop resistance. However, as a result of the diurnal variation in solar radiation, solar thermosyphon systems hardly operate in a steady mode. When the thermosyphon head is greater than loop resistance the flowrate increases and when it is less the flowrate decreases. Reverse flow may set in at night if the thermosyphon head becomes negative.

CRITERIA OF PERFORMANCE

Solar thermosyphon hot water systems have two main objectives. The first is to remove and transport as much energy as possible from the collector to the storage tank. The second is to achieve a required bulk storage tank temperature by the end of the operating period. These objectives give rise to two criteria of performance – system efficiency and temperature ratio. The system efficiency is defined as the energy delivered to storage divided by the incident solar radiation, for a specified time interval, i.e.

$$\eta = \frac{\int_0^t Q_u \, dt}{\int_0^t I_c A_c \, dt} \tag{1}$$

where η is the thermal efficiency,
Q_u is the energy delivery rate to storage,
I_c is the available irradiance on the solar collector,
A_c is the total collector surface area, and
t is time.

The temperature ratio (rT) may be defined as the ratio of the bulk storage temperature rise to the maximum possible rise.

For water heating systems, the boiling point of the heat transfer fluid may be used as the maximum limit so that

$$rT = \frac{T_{s,f} - T_a}{T_b - T_a} \tag{2}$$

where $T_{s,f}$ is the final bulk storage temperature,
T_b is the boiling point temperature of the heat transfer fluid, and
T_a is the ambient temperature.

In order to design a system with prescribed efficiency and temperature ratio, it is necessary to possess information (empirical, analytical or other) on the relations between Q_u, $T_{s,f}$ and other system variables. The major difficulty lies in the fact that Q_u and $T_{s,f}$ depend on a large number of factors: the size, shape and orientation of the collector as well as the fluid flow pattern through the collector; the diameter, length, spacing and geometry of the collector tubes, headers, riser and downcomer; the instantaneous flowrate which in turn depends on the instantaneous temperature distribution throughout the loop (thermosyphon head); the solar irradiance and the ambient temperature; the size and shape of the storage tank, the distance of the hot water inlet from the top of the tank and elevation of the tank above the collector; the insulation on the various components and, finally, the fluid properties throughout the loop.

The multiplicity of variables has made the study of solar thermosyphons exciting but difficult. Various researchers have proposed simplified models for estimating Q_u and $T_{s,f}$. Recently, a simple geometrical configuration (toroidal loop) has been studied with a view to understanding the basic processes [6].

TEST METHODS

In general, two types of tests are conducted on solar energy systems, including TSWH. The first type aims at the estimation of system parameters for the evaluation of economic viability. In this case, it is necessary to carry out testing over a reasonably long period of time, usually months or years, so that the system's performance during various seasons may be ascertained. The fractional energy savings, e, which is equivalent to the fraction of the load supplied by the TSWH system, has been used as the major performance indicator [7,9,10].

$$e = 1 - \frac{Q_a}{Q_c} \tag{3}$$

Q_a is the energy supplied by the auxiliary heater, for example, an electric booster which may be introduced to act as a measuring device. Q_c is the energy which would be supplied by a conventional heater to meet all the load requirements. Fractional energy savings is easy to measure fairly accurately since the load Q_c is specified and the auxiliary power Q_a can be measured with a wattmeter. Alternatively, the load supplied by the TSWH system may be directly measured by monitoring the load hot water flowrate and temperature together with the corresponding values for the cold water supply to the storage tank. This direct method is tedious and prone to large errors.

The second type of test, which is of more interest in this paper, aims at the instantaneous performance characteristics of TSWH systems. This test requires the instantaneous measurements of: temperatures throughout the system loop (and hence the thermosyphon head), the fluid flow rates in the various system components, irradiance on the collector aperture as well as the ambient temperature and wind speed. This type of test is thus required to validate dynamic models of TSWH systems. In practice, the temperature distributions, including collector plate and storage tank, are easily obtained with thermocouples and the irradiance can be measured with a pyranometer placed at the same elevation and inclination as the collector plane.

Measurement of the thermosyphon flowrate poses problems. Firstly, since the flowrate is driven by the solar irradiance which varies throughout the day, and may fluctuate considerably on cloudy days, the flow is inherently unsteady and may also fluctuate [11]. Secondly, the thermosyphon pressure which drives the flow is relatively low and the use of conventional flow meters will severely restrict the flow and thereby alter the conditions to be measured. A number of techniques have been used to minimize flow disturbance; these will be discussed later in section 6.

MAJOR EXPERIMENTS AND SIMULATIONS

Close (1962) was the first to conduct experimental and mathematical analysis of a solar thermosyphon water heating system [12]. His experiments indicated that the average collector temperature was only slightly higher than the average storage tank temperature and he presented a mathematical model for predicting mean system temperature and water mass flow rate. Close's mathematical model assumed equal collector and tank temperatures.

Ong (1974) improved Close's model by allowing the system properties (i.e. collector plate efficiency factor, heat loss coefficient, friction factor, etc.) to vary with temperature and flow rate [13]. Ong found his experimental results to be in disagreement with the assumption of equal mean temperatures for the various components in the systems. Ong (1976) further improved the mathematical model by rectifying the unrealistic equal mean temperatures assumption and breaking the system up into a finite number of sections, each individual section having a uniform mean temperature [14]. Ong also introduced overall heat loss coefficients for the connecting pipes in contrast with earlier studies which had assumed perfectly lagged pipes. Shitzer *et al.* (1979) tested a typical Israeli water heating system and observed essentially linear temperature distributions in both collector and tank for no draw [2].

Huang and Hsieh (1985) showed that for practical purposes, the instantaneous performance of TSWH systems can be described accurately by using the Hottel - Whillier - Bliss collector design equation with collector parameters which are obtained from standard collector testing procedures such as ASHRAE Standard 93-77 [15]. Furthermore, the thermosyphon loop resistance can also be measured independently as a function of flow rate. Huang and Hsieh also showed that in spite of the diurnal variations in solar radiation accurate results can be obtained by assuming constant hourly mean meteorological data, including incident solar radiation.

Kudish *et al.* (1985) carried out direct measurements of flow rate using an open solar thermosyphon system without storage tank and found a linear relation between flow rate and global solar radiation [1].

Vaxman and Sokolov (1986) simulated the influence of thermal insulation of the connecting pipes in a thermosyphon system and found a much stronger dependence of the 24-hour system efficiency on upper pipe insulation than on lower pipe insulation [16]. They found that even for situations where the storage tank was located above the collector, the upper pipe had to be properly insulated in order to suppress reverse flow at night.

TYPICAL EXPERIMENTAL RESULTS

Traditional Thermosyphon Set-up

Typical experimental set-ups

Some experimental results from Ong (1974) and Shitzer *et al.* (1979) are presented in Fig. 2. Ong employed a 1.4 m^2 collector with a 126 litre storage tank whose bottom was located about 75 cm above the top of the collector. Shitzer *et al.* employed two collectors having a total aperture of 3 m^2 with a 140 litre tank whose bottom was at the same level as the top of the collector.

The results of Shitzer *et al.* show that the daily variation in collector inlet and outlet temperatures is such that the two follow each other quite closely. Ong's results show that the average collector temperature can be much higher than the average storage tank temperature and during the late afternoon periods the reverse situation prevails.

Collector temperature rise

A comparison of the two curves for collector temperature rise, in Fig. 2, reveals no definite trend. The temperature rise in the collector of Shitzer *et al.* increases rapidly to about 16°C and then drops slowly. On the other hand the temperature rise across Ong's collector seems to follow the solar radiation; it increases to about 40°C (about 72°F) and then stays fairly constant until mid-afternoon after which it drops off almost exactly like the solar radiation.

Other researchers, including Lof and Close (1967) [17] have reported results which suggest a nearly constant temperature rise. Duffie and Beckman (1980) suggest a collector temperature rise of approximately 10°C for well-designed solar thermosyphon systems without serious flow restrictions [4]. Obviously this figure cannot be a universal prescription since collector temperature rise also depends on storage tank elevation. A very careful study is required to establish the factors which influence the actual value of the collector temperature rise and the degree to which it remains constant during the day.

Mass flow rate

The variation of mass flow rate during the day for both Ong (1974) and Shitzer *et al.* (1979) is also presented in Fig. 2. Ong's results suggest mass flow rate to follow solar radiation. Shitzer *et al.* draw a similar conclusion but their mass flowrate curve follows the solar radiation less closely. Experimental data from Huang and Hsieh (1985) [15], presented in Fig. 3, show that mass flow rate follows solar radiation very closely.

The three results give a good idea of the typically low flow rates encountered in solar thermosyphon systems. The maximum flow rate attained in Ong's system is about 0.005 litre/sec, Shitzer *et al.*'s is 0.017 litre/sec and Huang and Hsieh's is 0.023 litre/sec. The measurement of such low flow rates can be quite difficult. Ong (1974) estimated the flow rate by injecting a dye into the fluid stream and measuring the time taken to traverse a specified distance within a transparent tubing inserted in the system loop. Huang and Hsieh (1985) [15] also used a similar method with an estimated accuracy of ±5%. The method may be acceptable for laminar flow when there is no mixing; in transition and turbulent flow, the dye mixes with the flow and the time measurements may be grossly in error. Whatever the conditions, the apparatus must be calibrated, for example,

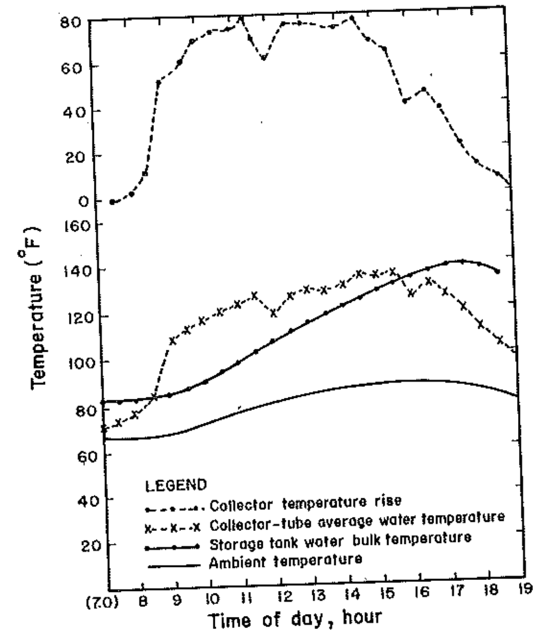

Fig. 2a. Daily variation of average collector water temperatures, storage tank bulk temperatures and collector temperature rise from Ong (1974).

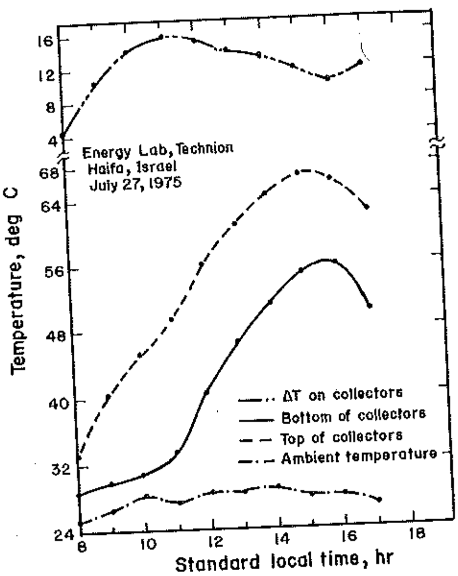

Fig. 2c. Daily variation of collector inlet and outlet temperatures, collector temperature rise and ambient temperatures from Shitzer *et al.* (1979).

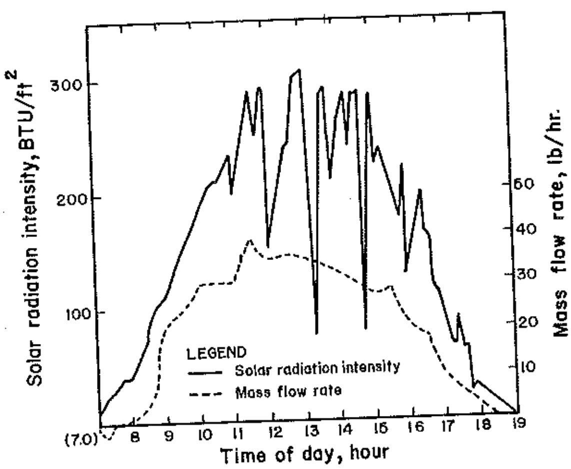

Fig. 2b. Daily variation in solar radiation and water flow rate from Ong (1974).

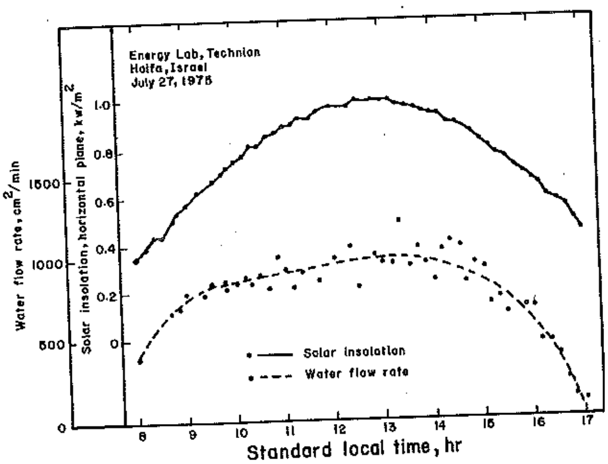

Fig. 2d. Daily variation in solar radiation and water flow rate from Shitzer *et al.* (1979).

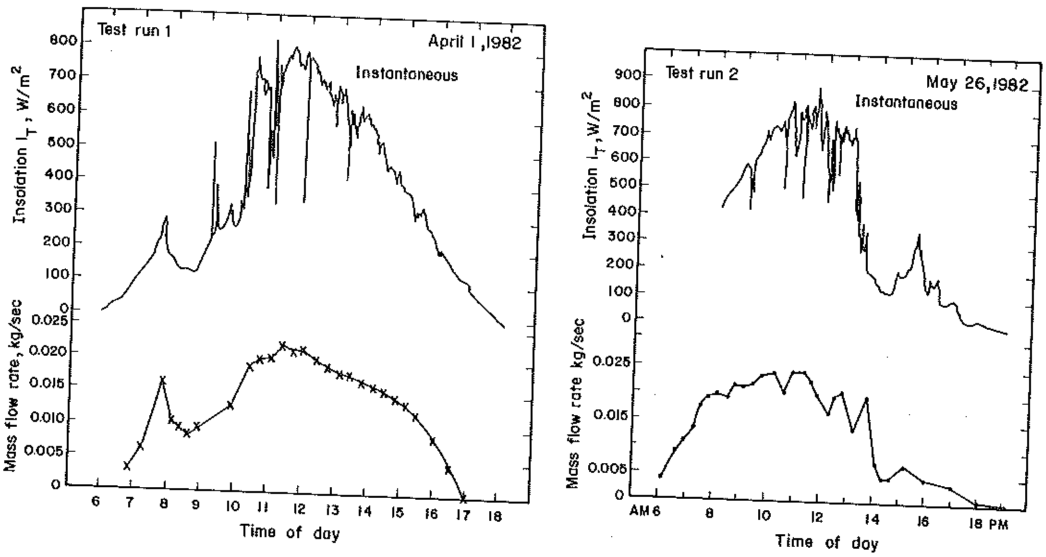

Fig. 3. Graphs of daily variation in solar radiation and water mass flowrate from Huang and Hsieh (1985).

by means of a measuring cylinder [10].

Shitzer *et al.* and also Norton and Probert (1984)[18] used specially designed thermal dissipa-tion meters, and Morrison and Ranatunga (1980)[19] employed a laser doppler anemometer to measure the laminar flow profiles. The accuracy of this latter method was estimated to be ±3%.

Young and Bergquam (1984) observed that although the laser doppler anemometer does not interfere with the flow, its use was limited by its high expense and complexity [20]. Instead, an energy balance on the storage tank was used to determine the system flowrate; the accuracy of the technique was estimated to be ±5%.

Open Solar Thermosyphon System

An interesting and relatively simple experiment which may be able to contribute considerably towards the understanding of solar thermosyphon hot water systems is that performed by Kudish *et al.* (1985) [1]. They employed a 1.89 m² Israeli collector in an open system as shown in Fig. 4. The experimental results obtained are also presented in Fig. 4. The collector temperature rise of 75°C and corresponding flowrate of 0.02 litre/sec make this system quite attractive indeed.

The collector inlet temperature for this system remains constant throughout the day. It is interesting to note that there is a linear relation both between flow rate and collector temperature rise and between flow rate and solar radiation. Comparison with the results presented above, for traditional (closed) solar thermosyphon systems, leaves a few questions unanswered. Why, for instance, would a constant collector temperature rise in the closed solar thermosyphon system yield a flow pattern similar to that of the radiation-dependent collector temperature rise in an open system? Such observations constitute a basis for further research.

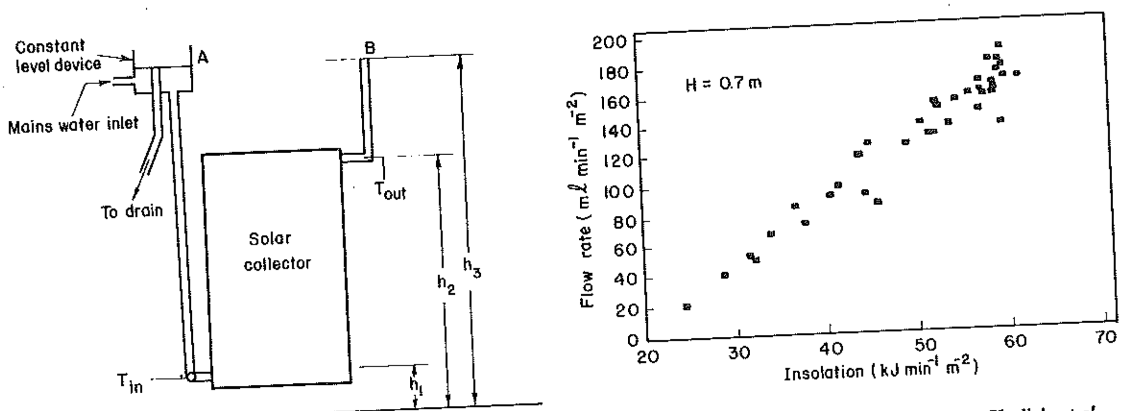

Fig. 4. Experimental set-up of the open thermosyphon system and graph of water flow rate vs insolation from Kudish *et al.* (1985).

GENERAL CONSIDERATIONS

Single- or Multi-Pass Systems

Solar thermosyphon systems may have very low flow rates such that the water in the tank passes through the collector only once during the whole day (single-pass). They may also have relatively high flow rates such that the water passes through the collector several times during the day (multi-pass). The advantage of single-pass systems is that, owing to their low flow rates, they have a larger temperature rise across the collector and so deliver hot water much earlier during the day than multi-pass systems. Furthermore, the inlet temperature and hence mean plate temperature remain low with consequent reduction in heat losses and gain in efficiency. The question now is, which system delivers more useful heat over the course of an entire day?

Tabor (1969) illustrated that the daily heat collected in single- and multi-pass systems is roughly the same [21]. Gordon and Zarmi (1981) confirmed Tabor's point for the case in which no hot water is drawn off during the period of solar energy collection [22]. However, Morrison and Tran (1984) conclude from their simulation studies that system performance improves as flow through the collector is reduced to approximately 1 tank volume per day [23]. This latter conclusion contradicts the earlier assertions in the literature and some experimental work will be required to settle the question.

Storage Tank Height

Ong's (1974) results presented in Fig. 2 correspond to a relative tank height of 75 cm while Shitzer *et al.*'s (1979) results correspond to zero relative tank height (i.e. bottom of tank at same level as top of collector).

Ong (1976) conducted experiments with varying storage tank height and obtained results which indicated that by increasing tank height flow rate increased. His results also further indicated that there could be an optimum height between tank and collector beyond which the system efficiency may decrease. Vaxman and Sokolov (1986) [16] observed that an increase in tank height increases flow friction and suggest that the optimum tank height is determined by the draw distribution; there is some indication in their paper that the optimum tank height may also depend on connecting pipe insulation.

Depending on the relative height of the storage tank, reverse flow at night may be suppressed or enhanced. Jansen (1983) suggests a minimum tank elevation of 25 cm [24]. Kreith and Kreider (1978) suggest a minimum of 30 cm [25]. McVeigh (1977) suggests a minimum of 60 cm [26]. Vaxman and Sokolov (1986) conclude from their simulation studies that the relative tank height should be in the range of 30-80 cm. The variety of recommendations for optimum tank height do create confusion and more conclusive studies will be needed to clarify the issue.

Tank-Collector Ratio

A variety of storage tank volumes and collector aperture areas have been reported in the literature. Ong (1974) used a Malaysian thermosyphon system consisting of a 126 litre storage tank and a 1.4 m² solar collector. Shitzer *et al.* (1979) employed a "typical" Israeli system having a storage tank volume of 140 litres and 2 solar collectors with a total aperture area of 3 m². Gordon and Zarmi (1981) mention a different "typical" Israeli system with a 120-litre tank and 2 m² collector. Chou and Ho (1983) report that residential units in Singapore have storage tanks between 100 and 300 litres with between 1.5 and 3 m² collectors [27]. Duffie and Beckman (1980) also report that for a family of four in Darwin, Australia, the recommendation for an all-year system is 450 litres of storage tank volume and 4 m² of collector aperture area.

A storage tank volume to collector aperture area ratio of 100 litres/m² seems, currently, to be the widely accepted ratio [27]. However, McVeigh (1977) recommends a rather low ratio of 50 litres/m². Storage tank volume to collector aperture area ratio has an effect on system performance. The lack of consistency in the various recommendations, therefore raises several questions. What happens to the collector temperature rise, for instance, in a given system if the collector aperture area is doubled? Further research will be needed to answer this and many other related questions.

Pipe Insulation

The influence of connecting pipe thermal insulation on system performance was studied by Vaxman and Sokolov (1986) and they found a much stronger dependence of the 24-hour system efficiency on upper pipe (riser) insulation than on lower pipe (downcomer) insulation. On the basis of their simulation studies they recommend that at least the upper pipe should be properly insulated.

It seems that, with the storage tank and upper pipe both well insulated, an optimum lower pipe insulation may exist. Further studies will be required here too.

Valves in Thermosyphon Systems

Reverse flow in solar thermosyphon systems is a matter of grave concern because it can cause dramatic reductions in the 24-hour efficiency. Huang and Hsieh (1985) installed a low-loss plastic check-valve in the collector in order to avoid reverse flow. From the previous discussions above it should be quite obvious that check valves would only be necessary where there are constraints on tank height. Where the storage tank is installed well above the collector, there should be no need for a check valve. Shitzer *et al.* (1979) also suggest the installation of an automatic valve to stop water circulation whenever the collector inlet temperature begins to drop. The drop in collector inlet temperature observed by Shitzer *et al.* was due, as they themselves acknowledged, to no insulation on the lower connecting pipe. For positive flow in a well insulated system, the existence

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of a temperature rise across the collector is a sign that useful energy is being collected and transferred to the storage tank. Therefore, it would not be beneficial to stop water circulation whenever the collector inlet temperature begins to drop, a phenomenon which occurs several times during the day whenever the solar radiation fluctuates.

SUMMARY OF NEEDED RESEARCH

A summary of the identified areas which need further research is as follows:

i. Daily variation, if any, in collector temperature rise and factors influencing this temperature rise.
ii. Daily mass flow rate variation in traditional (closed) solar thermosyphon systems vis-à-vis open systems.
iii. Single- or multi-pass systems for better heat delivery.
iv. Storage tank height for optimum 24-hour efficiency.
v. Effect of storage tank volume to collector aperture area ratio on system performance characteristics.
vi. Optimum downcomer (lower connecting pipe) insulation.

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