Research Paper

A Review on Two Phase Thermosyphon Heat Transfer: a Case Study on Solar Evacuated Tube Water Heater

Engineering

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ABSTRACT
Need for renewable energy sources, results in growing investment for solar collectors' use. Evacuated tube collectors are recently most widely used device to convert solar radiation into heat. In conventional applications they can provide energy for domestic hot water or space heating in combination with low water temperature systems. Several research articles have been published for representing the stratification of the fluid inside the tubes and the reservoir, as well as analytical models for the heat flow problem. Objective of this paper is to investigate the performance of the domestic solar water heater in which evacuated tubes are used as a solar energy collector with emphasis on two phase heat transfer analysis. This paper outlines the study of solar water heating with evacuated tubes, their operation characteristics and operating parameters are discussed.

INTRODUCTION

The oldest two phase flow heat exchanger used by mankind was certainly a cooking vessel for preparing meal by boiling. One of the first two phase flow heat exchanger for "public" use was proposed by Archimedes who invented a "steam Gun" for shooting bullets.

Food production was the dominant application of two phase flow heat exchanger until the beginning of the industrial age when James Watt invented his steam engine and chemical engineering started. From this time on a vehement development in two phase flow heat exchanger began continuing till today. From the Mechanical Engineering point of view two phase fluid flow is better than single phase, as it involves both laminar and turbulent flow characteristics. Hence its study has always remained interesting from heat transfer point of view. And mostly the benefit of phase change, namely the latent heat of evaporation and high heat flux densities were attractive to the designers of heat transfer equipment. Number of previous (researchers) workers have studied and analyzed fluid flow using conventional heating systems. In the present study attempt has been made to use nonconventional energy source.

2. LITERATURE SURVEY

2.1 Solar evacuated tube collector

E. Speyer [1], 1965, studied on solar energy collection using evacuated no tracking collectors with selective coatings. Each collector is a long glass lube, of five centimeter diameter, silvered in the lower portion, through which liquid flows. The efficiencies at different temperatures are calculated and the data are fitted by empirical equations.

G. L. Harding and T. T. Moon [2], 1982, studied on evacuation and deterioration of all-glass tubular solar thermal collectors. They developed two evacuation and degassing processes for all-glass tubular evacuated solar collectors. Collectors incorporating a sputtered graded metal-carbon on copper selective surface have been evacuated using either process, or then aged using various procedures, at temperatures of 300 to 375°C for up to 5000 h. Deterioration of vacuum in each collector was studied by measuring thermal conduction between the absorber tube and the collector envelope. No deterioration of the properties of the selective surface was observed after ageing.

F.O.Gaa et al. [3], 1997, investigated a numerical model and experimental observations of the inclined open thermosyphon by using finite difference algorithm to solve the velocity vector potential from Navier-stock equations. The model simulates flow in an inclined cylinder whose bottom and is sealed and whose top is connected to uniform temperature reservoir, a configuration of typical of evacuated tubular solar absorbers. The solution domain includes the cylinder only without the reservoir; therefore a special set of boundary conditions has been derived for vector potential at the top end which is a flow through surface. Steady flow is simulated at various combina-

tions of Rayleigh number, aspect ratio and mode of heating. An experimental set up has been developed in order to investigate the development of different flow patterns previously predicted by analytical and numerical workers, as well as to observe more closely the behaviour of the fluid at the at the orifice. the investigation shows that flow in a differently heated inclined open thermosyphon is typically bifilamental.

G.L. Morrison [4], 2004, presented measurement and numerical modeling of circulation rate in a water-in-glass evacuated tube solar collector as shown in Fig 2.1. The CFD model was validated against PIV measurements. For a specific collector configuration, circulation flow rate through the tubes is influenced by two factors, namely the radiation intensity falling onto the absorber surface and the temperature of the storage tank. At higher temperature operations, water viscosity is lower and the density gradient is larger for the same temperature difference. As the density gradient is the driving force of the natural circulation, the flow rate through the tube increases as tank temperature increases. Circulation rate through a single-ended tube mounted at 45° inclination over a diffuse reflector was investigated over a range of radiation intensities and tank temperatures.
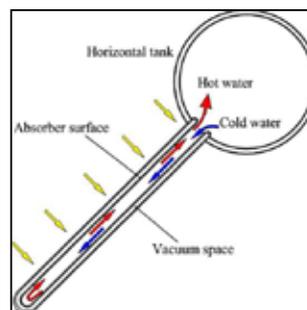

Figure 1: Natural circulation in water-in-glass collector

M. A. Islam et al. [5], 2005, have done experiment with a two-phase solar collector in which a flat-plate collector acts as an evaporator and a water tank acts as condenser. Each of the working fluids (Acetone and Methanol) boils in the flat plate collector, condenses in the water tank by releasing heat to water, and goes back to the flat-plate collector to be boiled again in order to repeat the cycle. The solar collector has been installed at BUET, Dhaka, Bangladesh. For each of the experiments during May-June 2003, absorber plate temperatures at different locations, coolant tube temperatures, inlet/outlet temperatures of working fluid, water temperature in the storage tank and solar insolation at a regular interval were recorded, and compared with those obtained using a conventional flat-plate collector. From the collected data the performance parameters such as instantaneous collector efficiency and heat removal factors have been calculated and analyzed
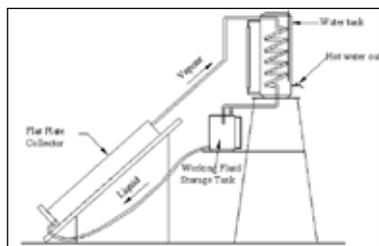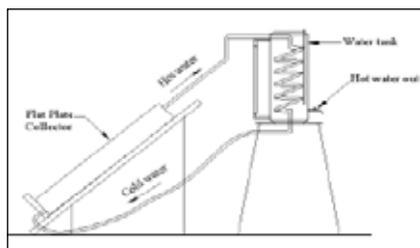
Figure 2: Two-phase solar collector

Figure 3: Single-phase solar collector

Louise Jivan Shah, Simon Furbo [6], 2006, have investigated the heat transfer and flow structures inside all glass evacuated tubular collectors for different operating conditions by means of computational fluid dynamics and that are based on a collector design with horizontal tubes connected to a vertical manifold channel. Three different tube lengths varying from 0.59 m to 1.47 m have been modeled with five different inlet mass flow rates varying from 0.05 kg/min to 10 kg/min with a constant inlet temperature of 333 K. Under these operating conditions the results showed that, the collector with the shortest tube length achieved the highest efficiency, and the optimal inlet flow rate was around 0.4–1 kg/min,

E. Azad [7], 2008, performed experiment on interconnected heat pipe solar collector. The prototype of interconnected heat pipe solar collector was designed and constructed. This design would reduce the production cost of the heat pipe panel and provides a better working condition for the system to act as thermal flux transformer compared to conventional heat pipe solar collectors. An analytical method was developed to examine the heat transfer occurring in the collector. The model was used to determine the collector efficiency, heat pipe temperature, water outlet temperature, and useful heat absorbed by cooling water. The validation of the model developed in this study has been confirmed by comparison of the results of the theoretical and experimental study.
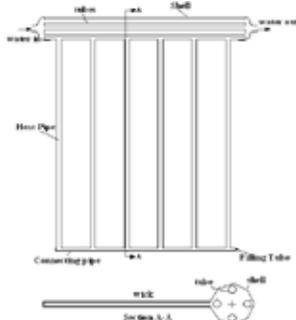

Figure 4: Interconnected heat pipes solar collector.

I. Budihardjo, G.L. Morrison [8], 2008, have studied the performance of water-in glass evacuated tube solar water heaters is evaluated using experimental measurements of optical and heat loss characteristics and a simulation model of the ther-mosyphon circulation in single-ended tubes. The performance of water-in glass evacuated tube solar collector systems are compared with flat plate solar collectors in a range of locations. The performance of a typical 30 tube evacuated tube array was found to be lower than a typical 2 panel flat plate array for domestic water heating in Sydney. Comparison shows that an evacuated tube system with 30 tubes has slightly lower energy savings than a two panel (3.7 m2) flat plate system. The performance of evacuated tube collector system was shown to be less sensitive to tank size than flat plate collector systems.

Raghavendra Prasada [9], 2010, has done an experiment of heat pipe in combination with evacuated tubes with water and methanol as working fluids in the heating system has been evaluated and compared using experimental measurements and simulation model to study the system efficiency. The test set up used for experimentation was inclined at an angle of 45° from horizontal. The study demonstrates that the water in heat pipe with evacuated glass tubes served as a good heat transfer medium. Results from experimentation are compared with computational results and there was a good similarity between experimental and computational results.
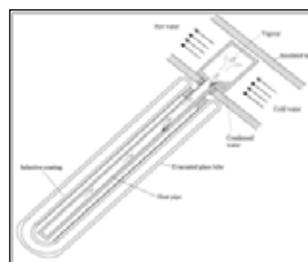

Figure 5: Arrangement of the experimental apparatus

The performance of all glass evacuated tube solar collector proved better in achieving higher range of efficiency theoretically (47.86%), closely followed by computational result (51.56%).

Liangdong Ma et al. [10], 2010, studied the thermal performance of the individual glass evacuated tube solar collector based on the energy balance by analytical method. The solar collector considered in this study is a two-layered glass evacuated tube, and the absorber film is deposited in the outer surface of the absorber tube. The heat loss coefficient and heat efficiency factor are analyzed using one-dimensional analytical solution. And the influence of air layer between the absorber tube and the copper fin on the heat efficiency is also studied. The results show that the function relation of the heat loss coefficient of the glass evacuated tube solar collector with temperature difference between the absorbing coating surface and the ambient air is nonlinear. In the different ambient temperatures, the heat loss coefficient of the solar collector should be calculated by different expressions.

A. I. Sato et al. [11], 2012, focused their work on the innovation to modify the solar evacuated tube collector and for that they proposed the study of solar water heating with evacuated tubes. To develop this work, a computational tool - computational fluid dynamics (CFD software - was used.
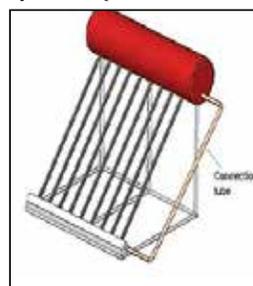

Figure 6: Schematic views of an ETC with modified geometry

2.2 Solar two phase thermosyphon heat transfer

R. S. Soin et al. [12], 1979, have evaluated the performance of a solar collector with a fluid undergoing phase change. The effect of insolation and the liquid level on the collector performance have been studied with acetone and petroleum ether 40- 60°C, and from the experiment they concluded that the efficiency increases with liquid level (rather markedly for lower liquid levels).
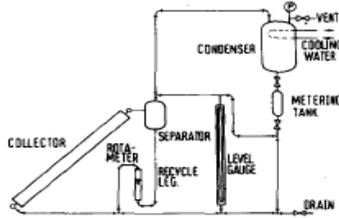

Figure 7: Experimental set up[12]

For low liquid levels, the entire tube length is not wetted by the liquid resulting in superheating of the vapor. Because of low heat transfer rate in the superheating region, the collector temperature rises. This increases heat losses causing low collector efficiencies. As liquid level is increased, a point is reached when superheating region disappears and liquid recirculation starts. Efficiency keeps on increasing till then as more and more portion of the tube is wetted by the liquid. After recirculation starts, the collector efficiency continues to improve slowly with increase in liquid level.
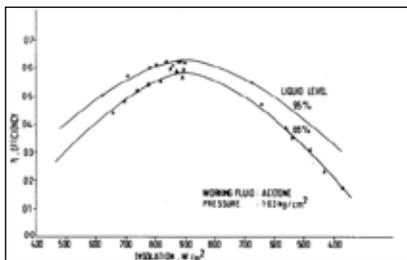

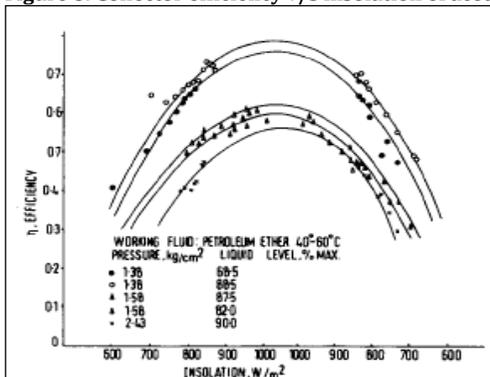**Figure 8: Collector efficiency v/s insolation of acetone**

Figure 9: Collector efficiency v/s insolation of petroleum ether

As the insolation increases, the efficiency increases because the heat losses remain constant as the collector plate is maintained at a constant temperature. Further the increased recirculation due to high insolation also increases the collector efficiency. This may be due to increase in boiling heat transfer coefficient.

H. A. Walker and J. H. Davidson [13], 1990, have worked on the thermal performance of a two-accumulator self-pumping solar water heater is characterized in a daily simulation. The passive vapor transport system operates in cycles, alternating between run, pressurizing, and pump phases. Three isother-

mal closed-system thermodynamic models characterize the operational phases of the system. The applicable conservation of mass and energy equations of each model are combined in the numerical simulation. Instantaneous temperature and heat transfer rates, as well as integrated energy quantities and thermal efficiencies, are compared to experimental values. The simulation reveals the impact of the duration of the pressurizing and pumping phases on overall performance. The volume and thermal capacitance of the components used during the pressurizing and pump phases should be minimized, while the insulation on those components should be maximized to optimize system performance. By Comparison of the simulation to experimental data they conclude that the self pumping, boiling collector system is potentially more cost effective, more reliable, and more thermally efficient than current solar heating systems.

Hichem Farsi et. al [14], 2003, analyzed an experimental and theoretical investigation of the two-phase closed thermosyphon (TPCT) behavior in transient regimes. Experimental results show two kinds of TPCT response. They focused on regular variations of operating system variables, where a mathematical model has been developed in order to obtain an analytical expression of the system response time. The dependence of this response time according to the various parameters is linked to geometry and heat transfer laws. The model can be considered as a simple and efficient tool for designing TPCTs in both transient and steady regimes.

Mehmet Esen, Hikmet Esen [15], 2005, have studied experiments were performed to find out how the thermal performance of a two-phase thermosyphon solar collector was affected by using different refrigerants.
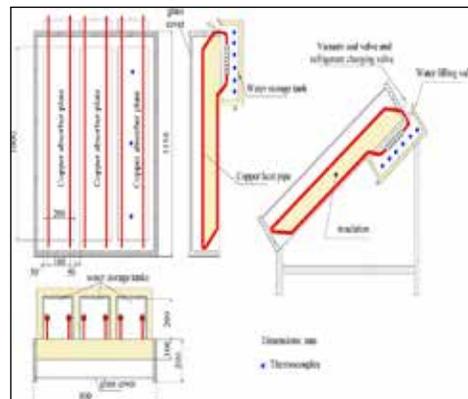

Figure 10: Experimental set-up[15]

Three identical small-scale solar water heating systems, using refrigerants R-134a, R407C, and R410A, were constructed and tested side-by-side under various environmental and load conditions. The performance of the system under clear-sky conditions has been investigated with and without water load. Detailed temperature distributions and cumulative collection efficiencies were determined and presented. The experimental results were compared to the results found in the literature and they showed good agreement.

Stéphane Lips, Josua P. Meyer [16], 2011, presented review on two-phase flow in inclined tubes, with specific reference to condensation. Tilting influences the flow patterns and thus the heat transfer and pressure drop during condensation in smooth tubes. However, few studies are available on diabatic two-phase flows in inclined tubes. Firstly, reviews convective condensation in horizontal tubes. Secondly, an overview is given of two-phase flow in inclined tubes. Thirdly, a review is conducted on condensation in inclined tubes. For convective condensation in inclined tubes that the inclination angle influences the heat transfer coefficient. The heat transfer coefficient can be increased or decreased depending on the experimental conditions, and especially the flow pattern.

A. Ordaz-Flores et. al. [17], 2011, have focused their work on experimental characterization and technical feasibility of a closed

two-phase v/s a conventional solar water heating thermosyphon for that Phase Change System (PCS) was designed and built. Tests in the PCS were performed using three working fluids: R134a, R410A and acetone, under the actual field conditions of Temixco, Mexico. Experimental data indicate that the PCS, loaded with either R134a or R410A, has equivalent performance than the DSWHS. However, high pressures and some difficulties to load the working fluid have to be dealt with.

Table.1- Comparison of PCS with DSWHS

Results	Phase Change System			DSWHS
	Acetone	R134a	R410A	Water
η	40.1 ± 1.6	51.5 ± 2.6	51.4 ± 0.9	51.4 ± 1.1
q_r [MJ]	32.1 ± 3.8	28.2 ± 1.9	27.6 ± 1.7	27.6 ± 1.7
q_u [MJ]	12.9 ± 1.8	14.5 ± 1.3	14.2 ± 0.9	14.2 ± 1.0
ΔT [K]	19.7 ± 2.8	21.7 ± 1.9	21.2 ± 1.3	21.2 ± 1.5
p[bar]	1.26 ± 0.20	13 ± 5	27 ± 7	p_{atm}
p_{max} [bar]	1.8	19.1	39.3	p_{atm}

Rounding of mean numbers was done according to standard deviation data.

The PCS working with acetone showed a slightly lower performance, but with the advantages of an easy load and low working pressure. R410A is not recommended to be used as working fluid because the high pressures reached in the system. Loading the system with R134a and R410A requires special care.

2.3 Two phase fluid flow conventional application
2.3.1 Plate heat exchanger:
Hitoshi Asano et. al [18], 2004, analyzed the two-phase flow characteristics in a plate heat exchanger, adiabatic air–water two-phase flows and R141b boiling two phase flows in a simulated plate heat exchanger with a single channel were visualized by a neutron radiography method, and two dimensional distributions and average values of void fraction were measured via some image processing methods. They have obtained results which are summarized as follows.

1. The liquid stagnation at the test section inlet strongly affected on the liquid distributions in the test section.
2. Liquid mixing in the ribbed channel was weak. For adiabatic air–water two phase flows, horizontal liquid distributions were kept to the test section outlet.
3. Average void fraction in the channel with ribs could be correlated based on the Drift flux model. The tendency on the dependency of flow patterns was the same as that in Ishii's model qualitatively.
4. For boiling two-phase flows, liquid distributions in the test section were affected by the inlet conditions. That is to say, liquid distributions were quite different whether working fluids were flowing into the test section as a two phase or a single-phase flow.

It can be stated from the above that the flow distribution in a ribbed channel was strongly affected by the inlet configuration and the inlet flow pattern. For example, for gas–liquid mixture at the inlet, it will be necessary to design the inlet configuration without liquid stagnation formation, such as without enlarging of conduit.

Kitti Nilpueng, and S. Wongwises [19], 2010, studied the air–water two phase flow characteristics including flow pattern and pressure drop inside a plate heat exchanger by experimentally.

A plate heat exchanger with single pass under the condition of counter flow is operated for the experiment. Three stainless steel commercial plates with a corrugated sinusoidal shape of unsymmetrical chevron angles of 55° and 10° are utilized for the pressure drop measurement. A transparent plate having the same configuration as the stainless steel plates is cast and used as a cover plate in order to observe the flow pattern inside the plate heat exchanger.
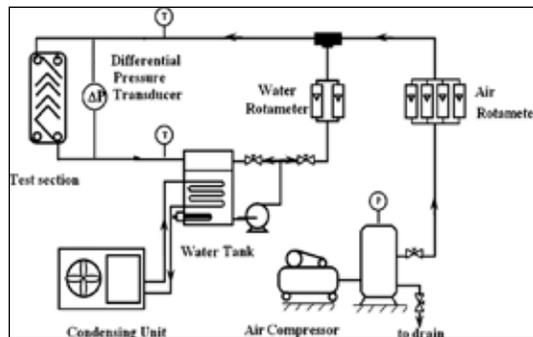

Figure 11: Experimental set-up[19]

1.2.2 cooling of radio base stations:
Rahmatollah Khodabandeh [20], 2004, investigated an advanced thermosyphon loop with extended evaporator and a condenser surface has been tested at high heat fluxes.
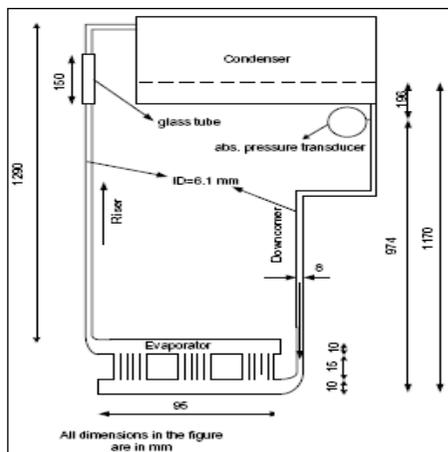

Figure 12: Experimental set-up [20]

The thermosyphon investigated is designed for the cooling of three parallel high heat flux electronic components. The tested evaporators were made from small blocks of copper in which five vertical channels with a diameter of 1.5 mm and length of 14.6 mm were drilled. The riser and down comer connected the evaporators to the condenser, which is an air-cooled roll-bond type with a total surface area of 1.5 m² on the airside. Tests were done with Isobutene (R600a) at heat loads in the range of 10–90 W/cm² to each of the components with forced convection condenser cooling and with natural convection with heat loads of 10– 70 W.

1.2.3. Multiphase flow in glass melter:
S.L. Chang et. al. [21], 2005, developed a multi-phase CFD code to simulate glass melter flow. The mass, momentum, and energy conservation equations are used to solve for local number density, velocity, and temperature for particles and bubbles respectively. In a similar manner, the conservation equations of mass, momentum, and energy of the glass-melt flow are used to solve for local liquid molten glass pressure, velocity, and temperature. The multiphase CFD code has been integrated into an overall glass furnace model (GFM), including the combustion space flow, radiation heat transfer, and glass melt flow. The model is being validated with experimental data obtained from in-furnace measurements. It have been demonstrated that the multiphase CFD code is capable of analyzing the heat transfer and flow patterns of both glass and batch flows as well as for investigating parametric effects for a commercial-scale glass melter at different operating/design conditions.

1.2.4. Two phase fluid flow in ducts:
S. Morales-Ruiz et. al. [22], 2009, presented a numerical study of the thermal and fluid-dynamic behaviour of the two-phase

flow in ducts under condensation or evaporation phenomena. The numerical simulation has been developed by means of the finite volume technique based on a one-dimensional and transient integration of the conservative equations (continuity, momentum and energy). The discretized governing equations are solved using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) which allows back flow phenomena. Special emphasis is performed on the treatment of the transition zones between the single-phase and two-phase flow.

1.2.5 Phase change thermal storage unit with shell and tube heat exchanger:

Monica F. Bonadies et. al. [23], 2012, has done optimization of the phase change thermal storage unit. For that they studied and examine a system integrating evacuated tube collectors with heat pipes with a storage unit using melted paraffin wax to store thermal energy.

A shell-and-tube heat exchanger is embedded within the paraffin wax storage with a volume of 0.23 m3. The heat exchanger includes two loops: one for glycol to transfer heat to the paraffin and one for water to extract heat from the melted paraffin. Although the paraffin has the benefit of being inexpensive and nontoxic, it has low thermal conductivity. Therefore, the heat exchanger has large brazed copper fins to extend areas of high thermal conductivity into the wax reservoir. To determine the benefit of the fins, wax and working fluid temperature data are taken from a constructed thermal energy storage unit and then used to verify a finite-difference one-dimensional analytical model of the unit. The maximum operating temperature of the glycol/water mix heat transfer fluid was approximately 65°C

when the fluid flowed at 3.78 l/min. City water at approximately 11.34 l/min was used to test the water heating capabilities of the unit.

3. CONCLUSION

Flat plate collectors using mild steel and copper plates as well as tubes have been accepted well in the commercial market. Large scale solar water heating systems based on this have been installed in dairy and textile industries in India for industrial applications. Similarly, number of hotels and at pilgrimage places hot water is obtained from solar systems for bathing purposes by installing solar systems on the terrace. Efforts have been made by many investigators to improve performance of the system by improving insulation of collectors and to increase collector efficiency. But such efforts increase weight of the system also. Evacuated tube collectors are a better alternative to minimize weight and heat loss from the collector. All over the world number of investigators have studied evacuated tube collector during the last three decades. The evacuated tube collector appears attractive from the efficiency point of view than the flat plate collector based on experimental and mathematical analysis. Moreover, two phase flow is advantageous than single phase flow for heat transfer purpose, which can be achieved easily using evacuated tube collector. Therefore, it is very much optimistic to say that the future researchers may explore much more in this area.

4. ACKNOWLEDGEMENT

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