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Performance Analysis of Solar Water Heater with Various Working Fluids

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Abstract

Optimized design of a solar water heater for effective heat transfer and the performance analysis was carried out in the present study. An experimental and theoretical performance of the system with an integrated heat pipe is evaluated for the same. The system uses a heat pipe with a wick to transmit heat from evaporator to the tank. The thermal behaviour of different parts of the system is analyzed. A sequence of tests are done on the heat pipe solar water heating system and thermosyphon water heating system to stimulate better configuration. The thermal efficiency of the system is optimized for maximum heat transfer using analytical techniques. Results show good thermal performance characteristics. Computation of various design parameters of heat pipe system related to the collection and consumption of solar energy are also conducted. Further, the exergy analysis and comparison of performance analysis of solar heat pipe collector with flat plate collector is also done.

Keywords: *Heat pipe, exergy analysis, Latent heat, Thermosyphon water heating system,*

1.0 Introduction

A. Heat Pipe and Operating Principles

Heat pipe is a high thermal conductance structure that transports heat from its one side to the other by using latent heat of vaporization. Hence this possesses higher thermal conductivity than solid conductors. The set up consists of an evaporator section and condenser section in the longitudinal direction. The inner part of heat pipe section consist of a container wall, wick structure and vapor space. Conventionally, heat pipe is a wrapped container containing the inner surfaces of which are coated with a capillary wick. The wick is saturated with vapor part and liquid part of working fluid. Vaporization of the working fluid occurs at the evaporator section owing to the applied heat. According to the pressure difference in the heat pipe, initially the vapor moves from evaporator to condenser and further it condenses releasing latent heat of vaporization. Diminution of liquid by evaporation drives the liquid-vapor to enter into the wick surface resulting in capillary pressure development. This capillary pressure pushes the compressed liquid back to the evaporator. That is, a continuous transport of latent heat of vaporization is attained in the evaporator-condenser section without drying out the wick. This course will last on condition that the flow path for the working fluid is not obstructed and an adequate capillary pressure is kept.

Fig.1 illustrates the longitudinal section of a conventional heat pipe with the components.

Compared to conventional convective system, the quantity of heat transfer as latent heat of vaporization is higher in heat pipe. Thus heat pipe is capable to transport a more heat with a small size. The temperature drip in the heat pipe is the summation of temperature drops at evaporator, vapor flow passage, and condenser.

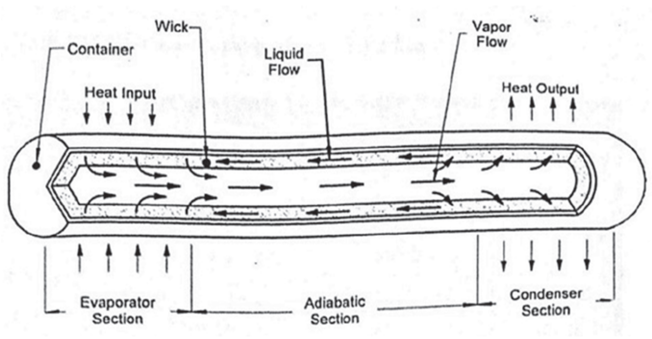

Figure 1: Components of Conventional Heat Pipe (Anandan and Ramalingam, 2008)

B. Wick Structures

The wick is provided to (1) the necessitate the flow passages for the departure of condensed liquid, (2) develop the required capillary pressure to drive the liquid, (3) as a heat flow path between the liquid vapor interface and the inner wall of the container. Mesh screen, fiberglass, sintered porous metal, and thin depressions cut in the interior surface of the container wall are used as the wick. Generally an effective wick structure requires pressure, and large internal pore for minimal liquid flow resistance.

C. Working Fluid

The working fluid is identified and selected considering the operating vapor temperature range. Among the number of possible working fluids that exist for the temperature band, most acceptable fluid is selected based on the following requirements:

- Agreement with mesh materials
- Thermal stability
- Wettability of wick and wall materials
- Medium range vapor pressure over the temperature range
- Elevated latent heat and thermal conductivity
- Low liquid and vapor viscosities
- More surface tension
- Adequate freezing or melting point

Thermodynamic considerations are also important as these are related to various anticipated restrictions to heat flow within the heat pipe. As the capillary force is the driving potential against gravity so high surface tension value required inside the heat pipe. The vapor pressure over the operating temperature should be enough to avoid large vapor velocities, which can create high temperature ascent and result in instabilities to flow.

2.0 Heat Pipe Design and Fabrication

a. Specifications

The following design specifications are arrived at based on calculations using design data book and availability of the material.

Diameter of heat pipe = 25.40mm Screen used = wrapped screen
Maximum temperature of the working fluid = 200°C
Length of heat pipe = lm
Length of evaporator section = 0.75m Length of condenser section = 0.25m

b. Selection of working fluid

The maximum temperature for the pipe is 200°C, water and methanol are suitable working fluids.

c. Selection of tube material

Since the working fluid is selected as water and methanol using design data book, the appropriate material for pipe is selected as copper.

d. Pro-E Design of Flat plate collector

Pro-E is a 3D CAD modelling application for design, analysis and manufacturing in Mechanical Engineering. Prior to fabrication of solar heat pipe, it was modelled in Pro-E for better understanding of the components, its orientation and arrangements. Figure 2 depicts the Pro-E design developed for the heat pipe.

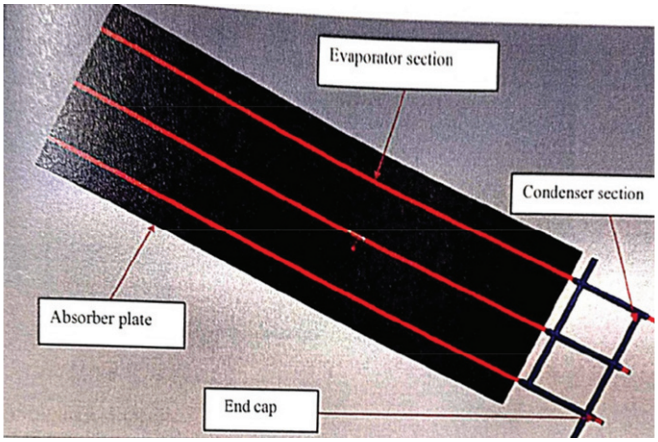

Figure 2: Pro-E Design of Solar Heat Pipe

Figure 3: Absorber plate of Heat Pipe

e. Fabrication of Circular Heat Pipe

The fabrication of circular heat pipe consists of fabrication of end cap, condenser section, absorber plate and collector.

T-joint and vacuum gauges are attached to the heat pipe. The fabrication of each part is explained below.

f. End cap of heat pipe

Three copper pipes (in diameter) are taken and threaded at both ends.

g. Condenser Section

Condenser tube (49mm outer diameter, 0.25m length) is fabricated by sheet metal operation. The joints of the sections are soldered.

h. Absorber Plate

The absorber plate is made of copper which is mechanically attached to heat pipe. The plate thickness is 1mm and width is 480mm and length is 750mm. The plate is coatedwith Matt black.

i. Collector

The material used to manufacture collector is aluminum. The dimensions of the collector are 760x500x50mm. Thermocol of 2cm thickness is used to insulate the space between collector case and absorber plate. Glass of 5mm thickness is attached to the collector. Eleven thermocouples are installed on this system. Out of these, nine are installed on the evaporator and two on the absorber plate.

j. Insertion of wick

The mesh size of wick is 100inch. The wire diameter of the wick is 0.017mm. The wick is cut in the required size. This is wound on a circular mandrel of size 15mm and inserted tightly in the heat pipe.

k. Collector of Heat pipe

Type	Flat plate
Dimension	1000mmx500mmx50mm
Working fluid	Water
Absorber plate material	Copper
Heat pipe material	Copper
Outer diameter of heat pipe	24.5mm

Design summary of the solar collector is given in Table 1.

Table 1: Design summary of solar collector

Thickness core diameter	3mm
Vapour core diameter	15mm
End cap thickness	3mm
Wick material	Copper
Wick screen mesh number	100in^-1
Wire screen wire diameter	0.0172mm
Case material	Aluminium (.5mm thick)
Insulation material	Thermocol (20mm thick)
Glazing material	Single glass plate (4mmthick)

l. Experimentation

Experiments are conducted using different working fluids. The heat pipe is charged prior to the start of experiment. The entire experimental set up assembled for the experimentation is illustrated in the photograph provided in Fig.4.

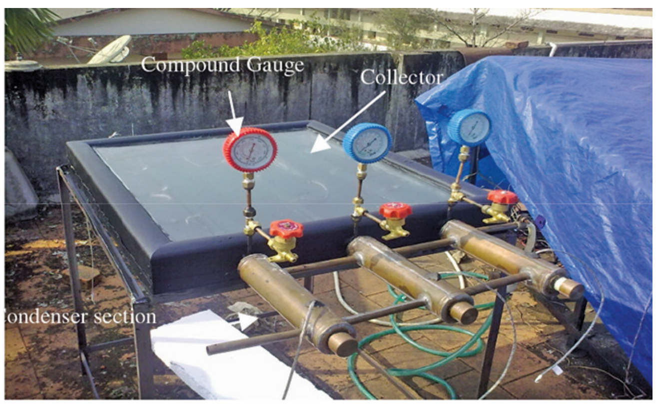

Figure 4: Assembled unit of experimental setup

m. Evacuation and Charging

Evacuation of heat pipe is recommended prior to chargingto avoid the formation of non-condensable or corrosive materials. It enables the removal of free gases in the pipe.

Each heat pipe is charged with 25ml of methanol. Further steps are described in the flow chart given below.

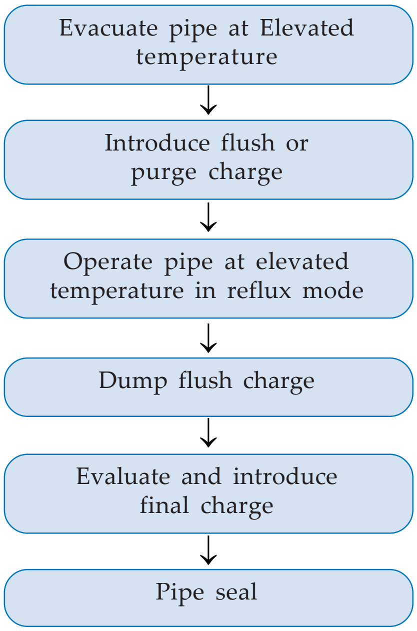

Figure 5: Steps for charging of heat pipe set up (modified from Dunn and Reay, 1978; chi, 1976)

3.0 Experimental Investigation

a. Procedure

The flow rate of cold water at the condenser section is kept persistent at 0.00217kg/s. The temperature at the condenser, evaporator and absorber sections are noted after steady state is obtained. Using thermocouple the temperature at inlet of the fluid (cold) and temperature at outlet of hot fluid from the condenser section was noted. The head difference in the manometer is noted to determine the flow rate. The procedure is repeated for the other two working fluids i.e. water and acetone. After these set of experiments, each heat pipe are slightly overcharged with 30ml of working fluids and the procedure is repeated to analyze the performance.

4.0 Energy and Exergy Analyses

Energy analysis of each components of the heat pipe is carried out by finding out the efficiency. Efficiency depends on the mass flow rate of water, heat gained by water irradiation and area of the collector as given in Equation 1.

$$\eta = \frac{Q_{useful}}{I_T \times A} \qquad \text{... (1)}$$

where, Q_{useful} – Heat gained by water

I_T – Irradiation

A – Area of the collector

Exergy analysis gives the amount of useful work done by the system. Exergy analysis of the heat pipe is determined separately for the evaporator section and condenser section. Analysis is based on mass and energy balance. Equations for the exergy analysis of both components are given in Equations 2 and 3.

$$(\eta)_{evap} = \frac{\dot{m}_v[(h_v - h_O) - T_O(s_v - s_O)]}{\dot{Q}_t\left(1 - \left(\frac{T_O}{T_{abs}}\right)\right) + \dot{m}_l[(h_l - h_O) - T_O(s_l - s_O)]} \qquad \text{... (2)}$$

where, $(\eta)_{evap}$ = Exergy efficiency of evaporator section

m_v = Mass flow rate of vapour (kg/s)

m_l = Mass flow rate of liquid (kg/s)

h_v = Enthalpy of vapour kJ/kg

h_l = Enthalpy of liquid kJ/kg

T_o = Ambient temperature (K)

S_v = Entropy of vapour (kJ/kg.K)

S_l = Entropy of liquid (kJ/kg.K)

S_0 = Entropy at reference temperature and pressure(kJ/kgK)

$$(\eta)_c = \frac{\dot{m}_{cw}[(h_2 - h_1) - T_O(s_2 - s_1)]}{\dot{m}_v[(h_v - h_O) - T_O(s_v - s_O)]} \qquad \text{... (3)}$$

where, $(\eta)_c$ = Exergy efficiency of condenser section

m_{cw} = Mass flow rate of condenser water (kg/s)

m_l = Mass flow rate of liquid (kg/s)

h_v = Enthalpy of vapour (kJ/kg)

h_0 = Enthalpy at reference temperature and pressure (kJ/kg)

S_1 = Entropy of cold water coming into the condenser section (kJ/kg.K)

S_2 = Entropy of cold water coming out from condenser section (kJ/kg.K)

S_0 = Entropy at reference temperature and pressure(kJ/kg.K)

h_1 = Enthalpy of cold water coming into the condenser section (kJ/kg.)

h_2 = Enthalpy of cold water coming out from condenser section (kJ/kg)

Substituting the values obtained from the experiments and other relevant properties corresponding to evaporator and condenser sections in Equations 2 and 3, the exergy efficiencies are evaluated. Detailed procedure is available in Vimal (2011).

5.0 Results and Discussions

Figure 6 depicts the variation of efficiency and solar radiation with time for a thermosyphon solar water heater. The variation of efficiency noted from 10am to 4pm is drawn and the maximum value of efficiency is obtained as 14.4% which is at 2.30pm. This is due to high solar emission and higher cold water outlet temperature in the condenser section.

Figure 7 shows the temperature dispersal along the longitudinal direction of heat pipe. From the experiment, the maximum value of the evaporator surface temperature is obtained as 77°C for water as working fluid 71°C for methanol as working fluid and 67.5°C for acetone solution as working fluid. But in the condenser section, there isn't any appreciable variation intemperature for the three working fluids. The average temperature along the condenser section is 50.75°C, 49.75°C, and 47°C for three working fluids along the heat pipe.

Figure 7 shows that 76°C, 70°C and 68°C are the maximum temperatures for three working fluids respectively. The average surface temperatures

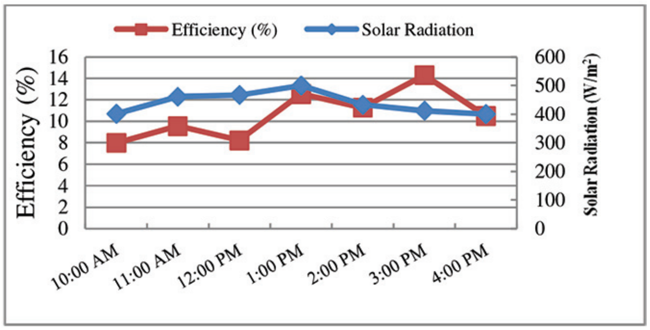

Figure 6: Efficiency and solar radiation with respect to time.

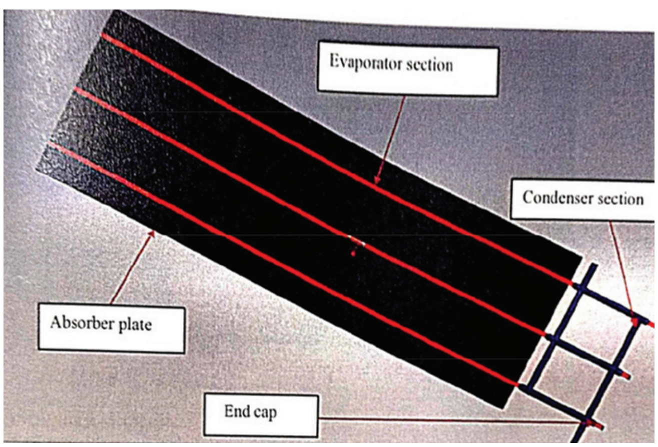

Figure 7: Variation of temperature along the heat pipe

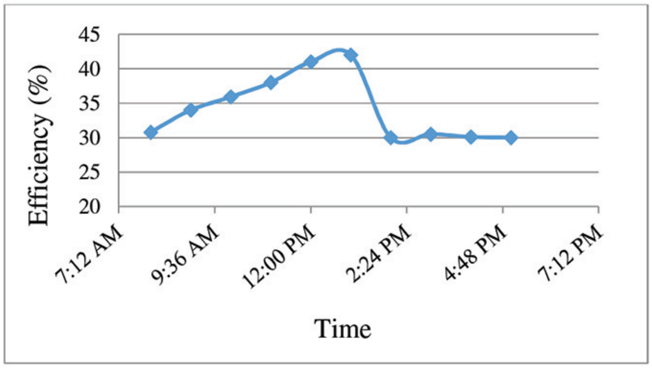

Figure 8: Thermal efficiency with time

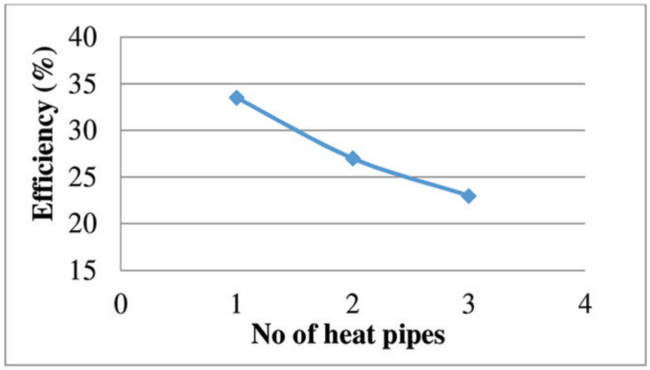

Figure 9: Thermal efficiency variation with no. of heat pipes

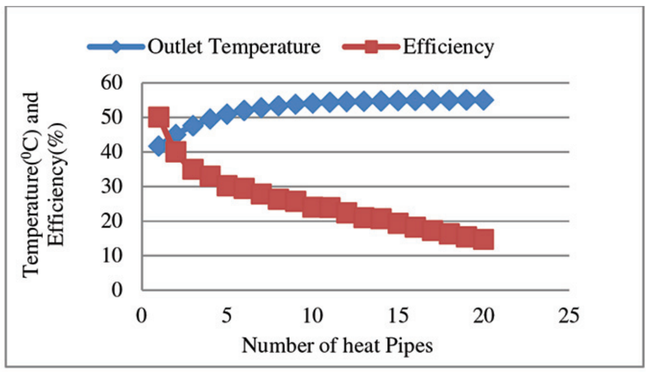

Figure 10: Temperature and efficiency variation with respect to quantity of heat pipes

obtained are 49.5°C, 47.5°C and 47.25°C for the three working fluids.

Fig.8 shows the thermal efficiency variation, when the working fluid is water. The hourly rate is quantified for the time between 9am and 5pm and the maximum system efficiency is 43% at 2pm.

Fig. 9 shows the variation of thermal efficiency with respect to heat pipes quantity. The figure shows that the efficiency which is due to the decrease in incremental variation of the temperature owed to the decrease in useful heat.

Figure 10 shows the variation of efficiency and temperature calculated theoretically when the number of heat pipes is changed. The stage efficiency is dec6reasing because the temperature difference is reducing in each stage. The variation of outlet temperature remains constantafter a certain number of stages.

VI. Conclusions

The heat pipe for solar water heating is fabricated. Experiments were conducted using the newly fabricated set up and the variation of temperature at different points along the longitudinal direction of the heat pipe is obtained. The experimental set up is able to establish the characteristics of solar water heating system, water inlet and outlet temperature and efficiency of the system etc. Experiments are also conducted in the existing set up which uses thermosyphon water heater using energy from sunlight. The efficiency of the thermo-syphon type water heater arrangement is obtained as 14%. For water as working fluid, the maximum thermal efficiency obtained using heat pipe with smaller area is 42% which is greater than that of the existing set up with larger area. Efficiency and analysis of heat pipe energy is conducted. The energy efficiency of the condenser is obtained as 24.3%. The energy efficiency of the evaporator is found to be 14% which can be improved by proper insulation of the collector. Experiments are conducted in the heat pipe solar water heating system using water, methanol and acetone as working fluids. For these working fluids used in the set up, temperature variation along the heat pipe is not found to be appreciable.

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