Experimental Study on Closed Loop Oscillating Heat Pipe for Different Filling Ratios

Shrekumar Soni1 and Dr. Ajit Kumar Parwani1, *

1Department of Mechanical Engineering, Institute of Infrastructure Research and Management (IITRAM), Maninagar (East), Ahmedabad, Gujarat, India - 380026

*ajitkumar.parwani@iitram.ac.in

Abstract. An experimental study was performed on Oscillating Heat Pipe (OHP) with closed loop structure. The capillary tube made up of copper of this OHP has inner diameter of 2.15 mm and thickness of wall is 1 mm. Different set of experiments were performed with filling ratios ranging from 30% to 100%, heating power ranging from 115 to 430 W at evaporator section and free convection condition at condenser section. The water has been considered as a working fluid. The thermal resistance was calculated for measuring the thermal performance of OHP. The changes in thermal resistance with heat input for various filling ratios has been carried out. The thermal resistance achieved lowest for 70 % filling ratio.

1. Introduction

Nowadays, the world is experiencing many challenges in solving heat transfer issues in various engineering systems. Transferring heat efficiently is one of the most important tasks in various engineering applications. Conventional heat transfer equipment cannot transfer heat effectively and also have moving parts. As compared to the best-known conductors like copper the OHP can transmit up to one thousand times more thermal energy with small temperature drop [1]. OHP or Pulsating Heat Pipe (PHP) does not need a wicking structure and has no moving parts hence OHP has silent operation and also requires minimum maintenance. Hence OHP can directly impact on cost, reliability and performance of various applications.

Figure 1 (a) and Figure 1 (b) shows schematic and experimental set up of closed loop OHP. A closed loop OHP is typically a meandering tube with small diameter and comprised of a serpentine channel [2]. A closed loop structure is formed when the two ends of tube are connected to each other. The tube is fully evacuated initially and then filled with the suitable working fluid partially. The working fluid taken in this study is water. The effects of surface tension force cause the formation of liquid slugs and vapour plugs. The liquid slugs of working fluid starts to evaporate as the heat is transferred from the evaporator section which causes the rise of vapour pressure inside the tube. This increase of vapour pressure in the evaporator section causes the vapour bubbles to expand that pushes the liquid towards the condenser. On the other side in the condenser section there is condensation of vapour bubbles which reduces the vapour pressure. This process is continuous between the condenser section and the evaporator section and an oscillating motion is set up within the OHP. The amplitude and the frequency of the oscillating motion within the tube will be dependent on the mass fraction of the liquid [3].
Various articles on experiment studies of OHP have been reviewed. Tong et al. [4] used charge coupled device (CCD) cameras for flow visualization in experiments of closed loop OHP having pyrex glass tubes with methanol as a working fluid. They found that the operation of closed loop OHP required a minimum critical power input which initiates fluid flow in tube. With the filling Ratio (FR) of 0.6 or 60% the circulation of the working fluid is possible which can transport heat from the evaporator to condenser section. During the start-up period large amplitude oscillations from the evaporator to the condenser occur and thereafter working fluid circulation is continuous. They also found the increase of circulation velocity with power input. Xue et al. [5] studied the full visualization and startup performance of an ammonia OHP. They found that for the operation of closed loop OHP with bottom heating mode and ammonia as a working fluid a very small startup power is required compared to water due to particular characteristics of ammonia. The OHP can start even when the evaporator temperature is only four centigrade higher than the temperature of condenser. Muraleedharan [6] performed experiments for flat heat pipes of different metals. He observed maximum capillary limit equal to 177 W for Aluminum flat heat pipe with axial grooves and composite wick with acetone as a working fluid. For stainless steel flat heat pipe, maximum capillary limit for acetone is 125 W and with water is 650 W. Experimental studies were performed on closed loop OHP by Zhang et al. [7] for heating powers ranging from 5 to 60 W and FR from 60% to 90% with pure natural convection condition and working fluid as water. The best overall thermal performance was determined to be 70% FR. Tanshen et al. [8] conducted experimentation on OHP charged with aqueous Al₂O₃ nanoparticles, MWCNTs and their hybrids. They studied phenomenon of heat transfer in terms of frequency of pressure fluctuation in OHP. They concluded that the best thermal performance for the OHP is obtained when the FR ranges from 50% to 60% and power input in evaporative section influences frequency of pressure fluctuation. The lowest thermal resistance is accomplished by the hybrid of aqueous Al₂O₃ and purified MWCNT. Mozumder et al. [9] conducted experiments on heat pipe using working fluids of three different types i.e. water, methanol and acetone and varied FR as 35%, 55%, 85% and 100%. They concluded that the heat transfer coefficient increases with FR of working fluid greater than 85% of volume of evaporator. They had shown with FR greater than 85% decreases the thermal resistance and it also reduces temperature difference across the evaporator and condenser. Baitule and Pachghare [10] carried out experimental analysis of closed loop OHP with variable filling ratio ranges from 0% to 100% in steps of 20%. The OHP was tested on four working fluids namely methanol, ethanol, acetone and water. They have found that the thermal resistance of closed loop OHP decreases with the increase of heat input. For the input power condition up to 48 W the thermal resistances are lowest for acetone and highest for water and above the 48 W the thermal resistance of acetone increases slightly. They have also found that 60% filling of OHP give the optimum result i.e. lower thermal resistance for each working fluid.

Some numerical studies have also been reported in the literature. Gupta and Parwani [11] performed CFD modeling of OHP in bottom heated mode. They have presented to achieve the lowest thermal resistance of 0.295 K/W during the working of OHP. Shafii et al. [12] presented analytical...
models for looped OHP with multiple liquid slugs and vapor plugs. They concluded that by increasing the diameter of the OHP, the total average heat transfer increases. The total average heat transfer significantly decreases with decreasing the temperature of the heating wall sections. Singh [13] performed CFD modelling and numerical analysis of performance of closed-loop OHP with alcohol as working fluid. He analysed that frequent oscillation with alcohol comes earlier than the water because alcohol having low specific heat will give cooling effect much earlier than water. He also observed that the oscillation will starts earlier with high value of heat flux input at evaporator section.

In this study, the water was used as a working fluid for OHP. The values for filling ratio taken were 30 %, 50 %, 70 %, 90 %, 100 %. The fill ratio is defined as the fraction by volume of the heat pipe, which is initially filled with the liquid [14]. The values of heat input have been taken by different hot water temperatures (i.e. 50 °C, 60 °C, 70 °C, 80 °C). The whole experimental setup is fabricated at Thermal lab of Institute of Infrastructure Technology Research and Management (IITRAM), Ahmedabad.

2. Experimental setup details
   The experimental apparatus of OHP fabricated for the current study is shown in Figure 1(b), with an overall width and height of 180 mm and 280 mm respectively. The OHP has a long capillary copper tube with an outside diameter of 4.15 mm and inside diameter of 2.15 mm. The bending radius of serpentine channel is 9 mm and total loop length is 2913 mm. The OHP set up is divided into three sections as shown in Figure 2 namely evaporator, adiabatic and condensation sections. The length of adiabatic section, evaporator section and condenser section can be changed. The arrangements for water in and out are given. The setup was levelled by level screws. The thermal load in the heating section was applied by acrylic flexiglass made hot water jacket of 300 mm × 65 mm × 120 mm. The thickness of the glass is 8 mm. The hot water bath is covered by a lid also. So, there is no such heat losses from the bath. The water is heated by heater rated 500 kW with different temperatures.

   The OHP is cooled down by natural convection. The condenser section is open to atmosphere. Below the condenser section, the tube is well heat-insulated by the thick glass wool covered by aluminium foil, forming the adiabatic sections. The OHP has contained a closed-loop pipe, with a charging port and a pressure gauge.

   The K type thermocouple wires are used with multichannel digital temperature indicator which has inaccuracy of ±1 % of Full Scale Deflection (FSD). The thermocouples i.e. T1 and T2 are connected to the water in and water out respectively. Four thermocouples i.e. T3, T4, T5, T6 are attached to the condenser section of OHP as shown in figure 2. The mass flow rate can be regulated by valve arrangement.

   Some amount of heat would have been lost from adiabatic section since there is not possible to achieve perfect insulation. Heat would be also lost from water bath, inlet and outlet pipes and other small leakages. Cumulative heat losses were estimated to be approximately 2-3 % of power input. Percent uncertainty in heat input was estimated to be approximately 1.0 %. The filling ratio uncertainty of an OHP was estimated to be ± 0.10 %. The dimensional accuracy was assessed to be ±1.0 mm. The accuracy of various measuring instruments is given in Table 1.

   Table 1. Accuracy of various measuring instruments

| Sr. No. | Measuring Instrument     | Accuracy   |
|---------|--------------------------|------------|
| 1       | Resistance Heater        | ±0.5 °C    |
| 2       | Thermocouple             | ±1.0 %     |
| 3       | The Steel Ruler          | ±1.0 mm    |
3. Experimental procedure
The experiments are performed with working fluid used as water. The evaporator section and adiabatic section length are same 100 mm while condenser section length is 80 mm. The volumetric flow rate is kept constant during the experiments. The water is heated by the heater. The hot water is then pumped in the hot water bath. The heat transfer takes place between the OHP and the hot water. The hot water in and hot water out temperatures are measured. Also, temperatures at condenser and evaporator section are measured. The transient tests on the heat pipe were conducted, in which heater is switched on and at regular intervals the increase of temperature readings are observed till the steady state is obtained. After reaching steady state condition, the temperatures reading at the six locations are measured. This procedure is repeated for other heat inputs and FR values. The level of filling ratios taken into consideration are 30%, 50%, 70%, 90 % and 100 %.

For the above mentioned FR the temperature readings at the six different locations on the surface of heat pipe has been noted after the steady state condition. Following equations are used for this study:

\[ Q_i = \dot{m}C_p \Delta T \quad (W) \quad (1) \]

\[ R = \frac{(\bar{T}_e - \bar{T}_c)}{Q_i} \quad (°C/W) \quad (2) \]

Where, \( Q_i \) (W) is heat input by the hot water, \( C_p \) is water specific heat = 4.184 kJ/kgK, \( \dot{m} \) (kg/s) is water mass flow rate = \( \rho \times \dot{V} \), \( \rho \) and \( \dot{V} \) are density (kg/m\(^3\)) and volumetric flow rate (m\(^3\)/s), \( \Delta T \) = Temperature drop between water in and water out, °C, \( R \) (°C /W) is OHP thermal resistance, \( \bar{T}_e \) is condenser average temperature, °C, \( \bar{T}_e \) = evaporator average temperature, °C, \( \bar{T}_e \) and \( \bar{T}_c \) can be calculated by,

\[ \bar{T}_e = \frac{(T1+T2)}{2}, \quad °C \quad (3) \]

\[ \bar{T}_c = \frac{(T3+T4+T5+T6)}{4}, \quad °C \quad (4) \]

4. Results
The results are shown by plotting graphs of thermal resistance (R) variations with heat input (\( Q_i \)) for different FR.

![Figure 2](image)

**Figure 2.** Thermal resistance variation with different heat inputs for (a) 30 % filling ratio (b) 50 % filling ratio

Figure 2 (a) shows that the values of thermal resistance ranging from 0.06813 °C/W to 0.15578°C/W with 30 % filling ratio, the minimum thermal resistance achieved is 0.06813 °C/W at 317.773 W of heat input. The thermal resistance is maximum for 172.374 W for 30 % filling. Figure 2 (b) shows that the values of thermal resistance ranging from 0.06757 °C/W to 0.1556 °C/W with 50 % filling ratio. The minimum thermal resistance achieved is 0.06757 °C/W at 317.4363 W heat input. The thermal resistance is decreased for each heat input with 50 % filling ratio than 30 % filling ratio.
Figure 3. Thermal resistance variation with different heat inputs for (a) 70% filling ratio (b) 90% filling ratio

Figure 3(a) shows that the values of thermal resistance ranging from 0.05857 °C/W to 0.1152 °C/W with 70% filling ratio, the minimum thermal resistance achieved is 0.005857 °C/W at 428.0264 W heat input. So, the thermal resistance is further decreased with increasing FR. Figure 3 (b) shows that the thermal resistance increased with FR varied from 70% to 90%. The minimum thermal resistance achieved is 0.0644 for 90% filling with 428.3021 heat input. For the case of 90% FR, the working fluid inside the OHP do not get sufficient space to generate bubbles, hence the performance of the OHP deteriorates. The thermal resistance is increasing from 116 W to 172.374 W for 30% to 90% filling ratio. Due to smaller increment of the heat input, it may not be able to increase the internal pressure of an OHP to circulate the working fluid flow efficiently. Because of this, there is the dominance of flow hindrance forces like surface tension forces, gravity forces etc. So, there is lesser heat transfer to the condenser hence lower values of condenser section temperature. Therefore, there is increase of thermal resistance for heat input from 116 W to 172.373 W.

Figure 4. Thermal resistance variation with different heat inputs for 100% filling ratio

At FR 100% the OHP operate as a single phase thermosyphon. Though oscillations do not occur under this condition, but substantial amount of heat transfer will still occurs due to circulation of liquid into the pipe by thermally induced buoyancy [12]. With increase in a heat input, the thermal resistance is decreased. The thermal resistance is minimum for 428.5756 W as shown in figure 4.

5. Conclusions
Experimental study was successfully conducted on a closed loop OHP. The water was used as a working fluid with FR 30%, 50%, 70%, 90%, 100%. The thermal performance was measured in terms of thermal resistance. Following are the conclusions drawn from this study:
The values of thermal resistance decrease with increase in filling ratio from 30% to 70% for each heat input. The thermal performance is maximum for 70% filling. After 70%, the performance decreases with increase in filling.

The experimentally determined optimal filling ratio is 70% for the water as a working fluid. In short, 70% filling ratio gives better result in terms of low thermal resistance and decrease in temperature difference across the condenser and evaporator.

The thermal resistance is increasing from 116 W to 173 W and then it starts decreasing for higher values of heat input (i.e. for 317 W and 428 W).

The performance of OHP with 100% filling (or thermosyphon) has shown better result than 90% filling in vertical position. The thermal resistance is continuously decreasing with increase in heat input.

References
[1] “Econotherm.” [Online]. Available: http://affinitas.com.sg/images/The Heat Pipe Advantage - 07.
[2] M. Kutz, “Mechanical Engineers' Handbook: Energy and Power”, Third Edition, vol. 4, John Wiley & Sons, Inc., 2005.
[3] D. A. Reay, P. A. Kew, and R. J. McGlen, “Heat Pipes: Theory, Design and Applications”, Fifth Edition, 2006.
[4] B. Tong, T. Wong, and K. Ooi, “Closed-loop Pulsating Heat Pipe,” Appl. Therm. Eng., vol. 21, no. 18, pp. 1845–1862, 2001.
[5] Z. Xue, W. Qu, and M. Xie, “Full Visualization and Startup Performance of an Ammonia Pulsating Heat Pipe,” Propuls. Power Res., vol. 2, no. 4, pp. 263–268, 2013.
[6] C. Muraleedharan, “Heat Transfer and Fluid Flow Studies on Flat Heat Pipe,” University of Calicut, 2001.
[7] X. M. Zhang, J. L. Xu, and Z. Q. Zhou, “Experimental Study of a Pulsating Heat Pipe Using fc-72, Ethanol, and Water as Working Fluids,” Exp. Heat Transf., vol. 17, no. 1, pp. 47–67, 2004.
[8] M. R. Tanshen et al., “Pressure Distribution Inside Oscillating Heat Pipe Charged with Aqueous Al2O3 Nanoparticles, MWCNTs and Their Hybrid,” J. Cent. South Univ., vol. 21, no. 6, pp. 2341–2348, 2014.
[9] A. K. Mozumder, A. F. Akon, M. S. H. Chowdhury, and S. C. Banik, “Performance of Heat Pipe for Different Working Fluids and Fill Ratios,” J. Mech. Eng., vol. M, no. 2, pp. 96–102, 2010.
[10] A. Baitule D and P R Pachghare, “Experimental Analysis of Closed Loop Pulsating Heat Pipe with Variable Filling,” Int. J. Mech. Eng. Robot. Res., Vol. 2, no. 3, 2013.
[11] A. Gupta and A. Parwani, “CFD Modeling for Thermal Performance of Closed Loop Pulsating Heat Pipe in Bottom Heated Mode,” Advances in Civil, Structural and Mechanical Engineering, 2017, pp. 46–50.
[12] M. B. Shafii, A. Faghri, and Y. Zhang, “Thermal Modeling of Unlooped and looped Pulsating Heat Pipes,” J. Heat Transfer, vol. 123, no. 6, p. 1159, 2001.
[13] A. K. Singh, “Numerical Analysis of Performance of Closed-Loop Pulsating Heat Pipe”, M.Tech. thesis, Department of Mechanical Engineering, National Institute of Technology Rourkela, June 2013.
[14] C. Fasula, “Oscillating Heat Pipes (OHP),” A Special Problems Paper, University of Rhode Island, May, 2009.