

Research Paper

PULSATING HEAT PIPE BASED HEAT EXCHANGER

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Waste heat, indeed, is generated in large quantities in various Process industries, nuclear reactors etc. Efficient heat exchangers are required to harness the waste heat from various potential sections. Pulsating heat pipes (PHPs) can be used to build heat exchangers to effectively harness most of the waste heat being generated in. Present research work includes design. Fabrication and testing of a liquid-liquid PHP based heat exchanger. Distilled Water has been used as the hot and cold fluids in the Heat Exchanger. The evaporator section of PHP was kept similar to the condenser section, while the adiabatic section was negligible. Various tests have been carried out to calculate the rate of heat transfer and effectiveness of a heat exchanger at different P1-P orientations, filling ratio, flow rates and inlet temperature of fluids. Heat transfer was found maximum at 40% filling ratio with effectiveness up to 0.40. Antigravity orientation (Evaporator up) showed considerable reduction in heat transfer to the cold fluid. Operating as well as oscillation characteristics of a close loop pulsating heat pipe have been investigated. Depending on the filled ratio, variation was found in the start-up temperature of the thermal oscillations inside the PHP. Besides the experimental work, this heat exchanger has been also modeled as heat pipe based heat exchanger with appropriate assumptions for evaluating its effectiveness. Satisfactory comparison of the experimental data with the developed model has been achieved.

Keywords: Pulsating heat pipes, Heat transfer, Heat exchanger

INTRODUCTION

Energy crisis has become one of the major problem all over the world, Especially the developed world needs more energy, countries like USA, consumes five times more energy than the rest of the world, however the energy consumption of developing countries like India and China is also on a rise at a very rapid pace.

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Waste heat from various potential sections. Pulsating heat pipes (PHPs) can be used to build heat exchangers to effectively harness most of the waste heat being generated.

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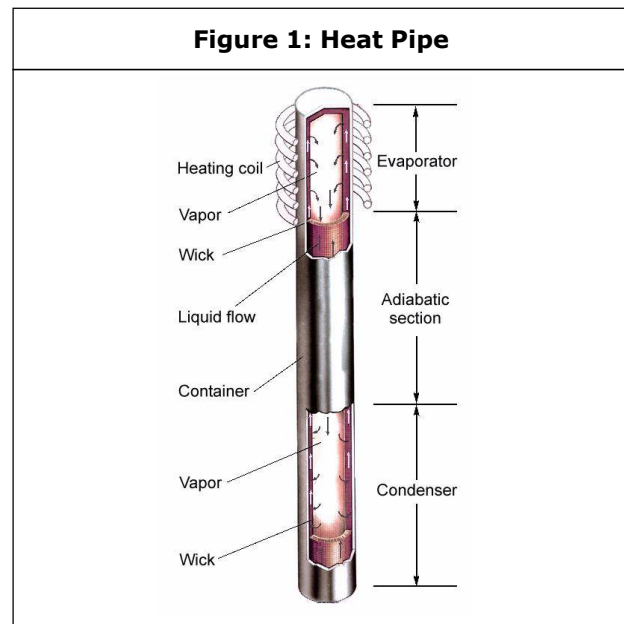
Present work is dedicated to design, development, testing and modeling of pulsating heat pipe based heat exchanger.

Heat Pipe Technology

The concept for a conventional capillary driven heat pipe was first suggested by R S Gaugler of General Motors. However, it was not until Grover G M who reinvented it, that its remarkable properties were appreciated and serious development began.

A heat pipe is a heat transfer mechanism that can transport large quantities of heat with a very small difference in temperature between the hotter and colder interfaces. The areas of application of heat pipes include heat exchangers and boilers, electrical and electronics equipment cooling, medical devices, temperature control in satellites, solar heating systems, isothermal furnace liners, black body radiators, and special heating and cooling tasks in various industrial applications. Variable conductance heat pipes, gravity assisted heat pipes, heat pipe thermal diodes, rotating heat pipes are some such examples of heat pipe configurations. Another category of heat pipe is micro heat pipe having typical diameters of 1 mm or less have already been introduced about 20 year ago and known for thermal management in microelectronics cooling.

A conventional heat pipe consists of a sealed metallic container having a capillary wicking material at inner surfaces. In a heat pipe there are mainly three sections: evaporator, adiabatic section and condenser as shown in Figure 1. At the heated end of heat pipe the working fluids inside the pipe evaporates and thus increase the vapour pressure inside the cavity of the heat pipe. The vapour pressure over the hot liquid working fluid at the hot end of the pipe is higher than the



equilibrium vapour pressure over condensing working fluid at the cooler end of the pipe, and this pressure over condensing working fluid at the cooler end of the pipe, and this pressure difference drives a rapid mass transfer to the condensing end where the excess vapour condenses, releases its latent heat, and warms the cool end of the pipe. In practice, the speed of the vapour through the heat pipe is dependent on the rate of heating/condensation. The condensed working fluid then flows back to the hot end of the pipe. In the heat pipes containing wicks, the fluid is returned by capillary action.

MATERIALS AND METHODS

The experimental set-up (PHP based liquid-liquid heat exchanger) was designed to fulfill the following research objectives:

- (i) To evaluate the rate of heat transfer from hot fluid to cold fluid.
- (ii) Design of the experimental setup allowed for the following parametric investigation:
 - (a) Filling ratio of PHP working fluid

- (b) Flow rates of the heat exchanging fluids
- (c) Fluid Inlet temperatures of the heat exchanging fluids
- (d) PHP orientation

A brief description of the peripheral support devices used in the experiments is elaborated first. These devices are PC based data acquisition system, vacuum pump. Filling/charging micro-metering valve, constant temperature baths. Thermocouples, etc. There after. Brief description and procedure of the main experimental set-up follows.

VARIOUS PERIPHERAL DEVICES

Various peripheral devices various peripheral devices, as discussed above, were used to perform the experiments. A short description of these support systems is given below.

Temperature data acquisition has been done using PC interface card model 'NI cFP 1804' from M/s National Instruments. For temperature measurement this high precision computer based card can convert voltage signals generated by thermocouples into corresponding value of temperature in digital form.

Constant temperature baths (Figure 2) are the devices used to maintain or circulate liquid (generally water or oil) at constant temperatures. Two such baths. Refrigerated/Heating Circulator F34-ME (accuracy: $\pm 0.01^\circ\text{C}$. flow rate: 11-16 l/min) and Heating Circulator SL-26 (accuracy: $\pm 0.01^\circ\text{C}$. flow rate: 22-26 l/min) supplied by M/s Julabo. Were used to maintain water at constant temperature at inlet in both the chambers of heat exchanger.

Six K-type precision fine wire thermocouples (Figure 3) supplied by OMEGA Engineering Inc... were used to find temperatures at different locations in the experimental setup. Accuracy of the thermo couples was $\pm 0.1^\circ\text{C}$. Out of these, four thermocouples were used to get the temperatures at the inlet and outlet of the two chambers of the heat exchanger. Remaining two was attached at the midpoints in the evaporator and condenser sections. For fixing the thermocouples properly on the PHP copper tube, thermal cement was used.

A Micro-Metering valve (Figure 4) supplied by M/s Upchurch Scientific. USA was used for evacuation, filling/charging and metering of working fluid in the PFIP. It also helped in maintaining a specified volume of working fluid inside the PHP. The Micro-Metering Valve was

Figure 2: Constant Temperature Bath



Figure 3: K-Type Thermocouples



designed for placement in the flow system which exhibits control on the amount of fluid transfer, as low as 3.5µL/min, with a through hole of 0.5 mm. It is made of sturdy Polyether Ether Ketone Polymer.

For creating vacuum inside the PHP a rotary vane type pump coupled with turbo molecular pump with a vacuum gauge were employed. The Rotary-Vane Pump VARIAN DS 102 (Figure 5) is highly reliable, delivering excellent vacuum performance and provides high pumping stability for light gases, low noise, minimal oil back streaming and long operating life. By using this pump, ultimate vacuum of mbar can be achieved. The turbo-molecular pump VARIAN Turbo V-70 (Figure 6), having the speed of 75000 rpm, is a pump which can create ultimately very high level

of vacuum up to 10 mbar. Start-up time of this pump is less than 60 second. For effective and safe use of turbo-molecular pump, initially a certain level of vacuum is required. To fulfill this objective first of all vacuum is created with the help of rotary vane type pump and then the start turbo-molecular pump is started. Shut down of the pumps should be done in reverse manner.

A multi-gauge (Figure 7) was attached to the pumps to indicate the order of vacuum reached in the units preferred.

The schematic diagram of the entire setup is shown in Figure 8.

For hot water flow, one of the constant temperature baths is connected to one of the

Figure 4: Micro Metering Valve

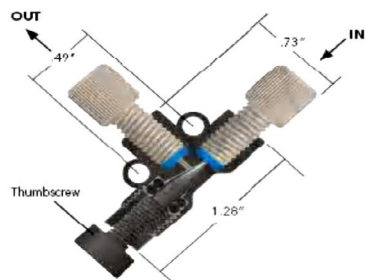


Figure 5: Rotary Van Pump



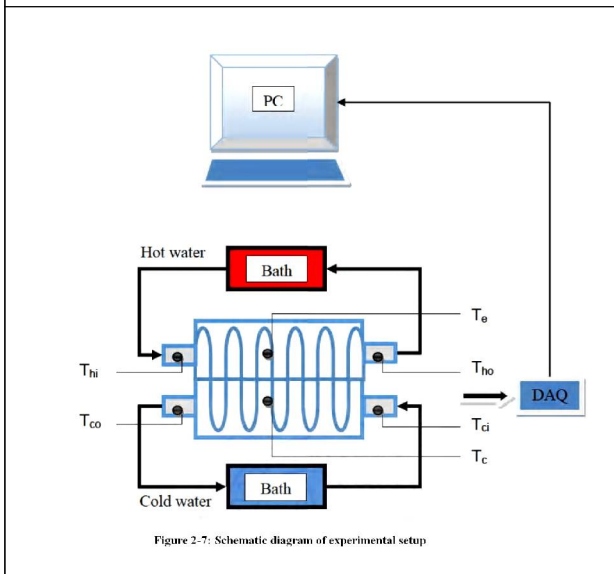
Figure 6: Micro Metering Valve



Figure 7: Rotary Van Pump



Figure 8: Integrated Experimental Setup



chambers of the heat exchanger. Similarly for cold water flow, the other chamber is connected to another constant temperature bath. Thermocouples at six different locations are connected as shown in Figure 8. Out of these, four thermocouples are connected to the inlet and outlet of both the chambers of the heat exchanger. Remaining two is connected to the evaporator and condenser sections of the PHP. For acquiring temperature data from the thermocouples. VI Logger is connected through the computer Heat Exchanger is provided with proper polyurethane foam insulation of thickness 40 mm to minimize the heat losses.

RESULTS AND DISCUSSION

The main aim of the experimental investigations was to better understand the thermal performance of PHP based liquid-liquid heat exchanger in terms of heat transfer and development of an analytical model to theoretically predict its effectiveness. In this chapter, first of all we will discuss about experimental procedure and thereafter thermal performance of heat exchanger and its modeling will be discussed.

The temperature recorded from cold water at inlet (T_{ci}), cold water at outlet (T_{co}), hot water at inlet (T_{hi}), and hot water at outlet (T_{ho}), of heat exchanger respectively.

1. At 0 % filling ratio (dry test)

Dry test was performed to calculate the heat transfer to the cold fluid that was occurring through the solid stainless steel wall, splitter plate and the dry copper tubes collectively. Table 1 shows the rate of heat transfer at three different temperatures of inlet hot water.

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	36.5	60	59.65	97
35	37.4	75	74.6	145.6
35	37.95	85	84.55	190.7

2. At 40 % Filling Ratio

(a) Bottom heating position (Gravity orientation)

PHP with 40 % ethanol showed maximum amount of heat transfer as compared to other filling ratios at respective inlet hot water temperatures (Table 2).

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	39.8	60	59.3	310.1
35	49	75	73	915.7
35	55.8	85	82	1339.3

(b) Top heating position (anti-gravity orientation)

Heat transfer was reduced to a great extent in case of evaporator-lip position (antigravity) (Table 3).

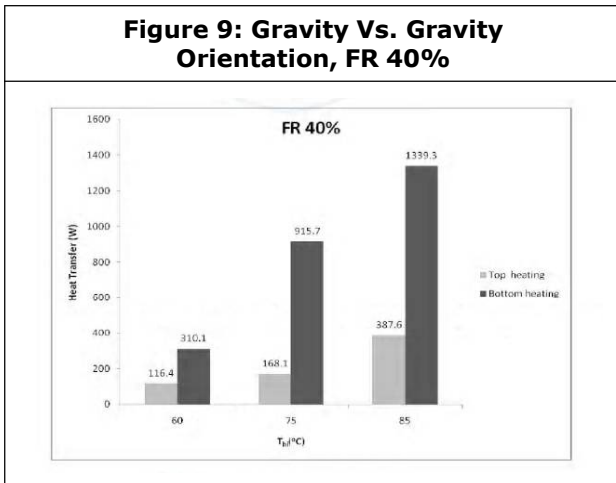
Figure 9 shows the comparison of heat transfer through the PHP in anti-gravity orientation and gravity orientation with 40% filling ratio.

Table 3: Important Temperatures of CLPHP, Anti-Gravity Orientation, FR 40%

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	36.8	60	59.7	116.4
35	37.6	75	74.5	168.1
35	41	85	84	387.6

Table 5: Important Temperatures of CLPHP, Anti-Gravity Orientation, FR 60%

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	36.9	60	59.65	122.8
35	37.8	75	74.5	181
35	38.4	85	84.4	219.7



As can be seen in Figure 9, heat transfer to the cold water in gravity-orientation was much larger than the anti-gravity orientation at all the three values of hot inlet temperature.

3. At 60 % Filling Ratio

(a) Bottom heating position (Gravity Orientation)

Heat transfer was slightly less in this filling ratio as compared to 40% (Table 4).

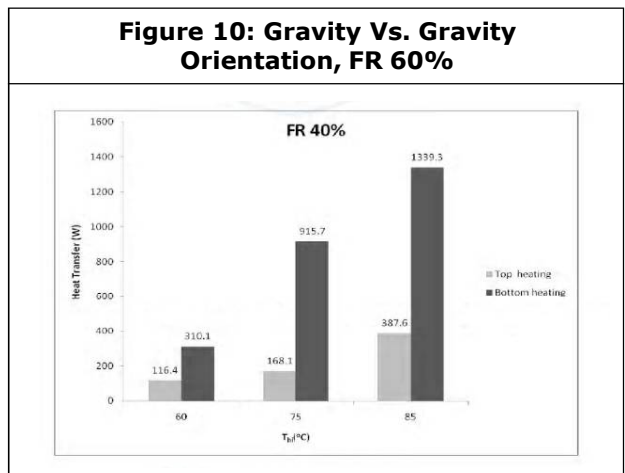
(b) Top heating position (anti-gravity orientation)

Table 5 shows the rate of heat transfer at three different temperatures of inlet hot water.

Table 4: Important Temperatures of CLPHP, Gravity Orientation, FR 60%

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	38.5	60	59.4	226.2
35	47	75	73.25	774.2
35	53.2	85	82.35	1172.5

Figure 10 shows the comparison of heat transfer through the PHP in anti-gravity Orientation and gravity orientation with 60% filling ratio.



As can be seen in above figure, heat transfer to the cold water in gravity-orientation was much larger than the anti-gravity orientation at all the three values of hot inlet temperature.

4. At 80% filling ratio

(a) Bottom heating position (Gravity Orientation)

Heat transfer was least at 80% filling ratio in bottom heating position as compared to other filling ratios (Table 6).

Table 6: Important Temperatures of CLPHP, Gravity Orientation, FR 80%

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	39.5	60	59.25	310.1
35	43.5	75	73.7	548.7
35	46.5	85	83.25	742

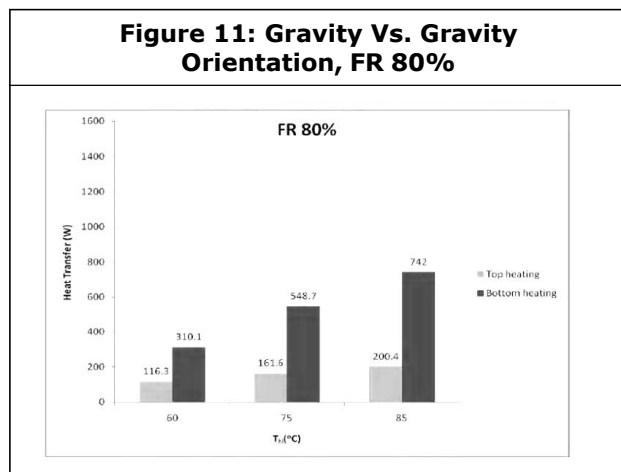
(b) Top heating position (Anti-gravity orientation)

Heat transfer was least in this case as compared to all other filling ratios (Table 7).

Figure 11 shows the comparison of heat transfer through the PHP in anti-gravity orientation and gravity orientation with 80% filling ratio.

Table 7: Important Temperatures of CLPHP, Anti-Gravity Orientation, FR 80%

T_{ci} (°C)	T_{co} (°C)	T_{hi} (°C)	T_{ho} (°C)	Q(W)
35	36.8	60	59.6	116.3
35	37.5	75	74.55	161.6
35	38.1	85	84.45	200.4

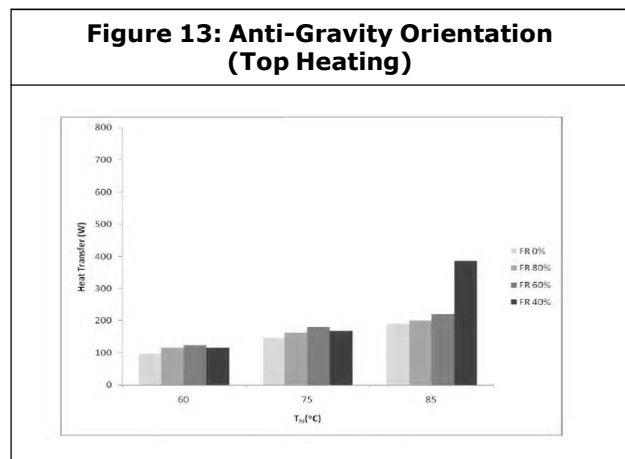
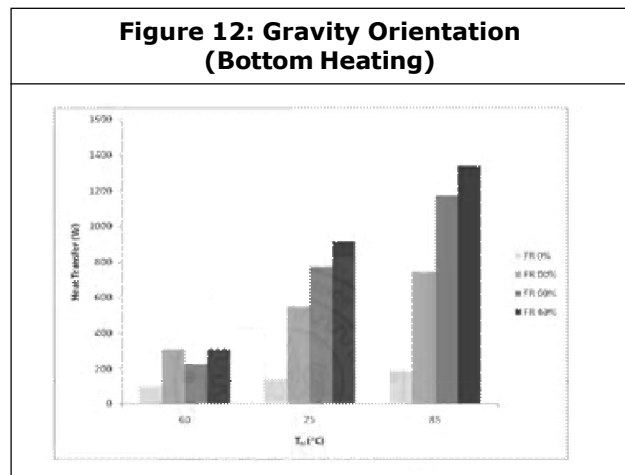


As can be seen in above figure, heat transfer to the cold water is higher in gravity orientation than in anti-gravity orientation but not as high as compared to other filling ratios.

Figures 12 and 13 shows the rate of heat transfer at different values of inlet hot temperature for different filling ratios in gravity and anti-gravity orientations.

As can be shown in above figure, heat transfer is maximum at 40% FR and minimum at 0% FR.

As can be seen in above figure, heat transfer is almost similar in anti-gravity orientation all filling



ratios. Sudden rise in heat transfer at FR 40% at 85°C is due to the temperature oscillations inside PHP at that temperature.

CONCLUSION

1. Heat transfer with working fluid filled inside PHP was much higher than dry PHP.
2. For the low values of heat throughput PHP in gravity supported orientation performs better than PHP in anti-gravity.
3. In general, PHP performs better at the volumetric filling ratio 40% than that of 80%.

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