Heat Pipe Based Heat Exchanger: A Review

Dnyaneshwar G. Chavhan[1] Pramod R. Pachghare[2]
[1]M.Tech Student [2]Assistant Professor
[1,2]Government College of Engineering, Amravati

Abstract— Heat pipes are two-phase heat transfer devices with high effective thermal conductivity. Due to the high heat transport capacity, heat exchanger with heat pipes has become much smaller than traditional heat exchangers in handling high heat fluxes. With the working fluid in a heat pipe, heat can be absorbed on the evaporator region and transported to the condenser region where the vapor condenses releasing the heat to the cooling media. Heat pipe technology has found increasing applications in enhancing the thermal performance of heat exchangers in heating the vehicle compartment in cold countries, to recover heat from exhaust air in mini- dryer, in thermal radiator, in waste heat recovery from waste water.

Keywords: Pulsating heat pipe, Heat exchanger, Thermal resistance, Effectiveness, passive two-phase heat transfer, wire on tube, dryer.

I. INTRODUCTION

Presently there are several different techniques for transferring heat between high and low temperature fluids. However the method which has received a significant amount of attention and research is the heat pipe heat exchanger (HPHE). This device is similar to a liquid coupled indirect transfer type heat exchanger except that the heat pipe heat exchanger employs heat pipes or thermosyphons, which use the evaporation and condensation of a working fluid within a heat pipe as the major heat transfer mechanism from the high temperature to low temperature fluid, and do not require an external pump to circulate the coupling fluid. Most HPHE's use thermosyphons because they have a higher maximum heat transport capacity and are easier to manufacture than heat pipes. However, thermosyphons which use gravity as a means to return the condensate back to the evaporator require at least a 5^o elevation of the condenser above the evaporator. In cases where the evaporator must be elevated above the condenser heat pipes can be used. Heat pipe heat exchangers are normally used as waste heat recovery systems, where the scavenged heat is available for space heating steam generation or to preheat combustion air in fossil-fired power plants and in process furnaces.

Heat pipe heat exchanger is similar to finned tube heat exchanger. In which the heat exchanger are divided into two separate section i.e. evaporator section and condenser section. Separated by splitter plate, as shown in fig.1. However, the tube is a heat pipe, and hot and cold fluid flow continuously in separate parts of the exchanger, heat is transferred from the hot fluid to the evaporation section of the heat pipe by the convection. The thermal energy is then carried away by the vapor to the condensation section of the heat pipe, where it transfers heat to the cold fluid by convection.

To understand the pulsating heat pipe based heat exchanger, we must know about pulsating heat pipe. Pulsating heat pipe is explain as follows,

A. Pulsating heat pipe

Pulsating heat pipes (PHPs) or oscillating heat pipes (OHPs) are relatively young members in the family of heat pipes. Initially it is developed by Akachi in the 1990s and can be divided into 3 groups: (a) closed loop PHP without check valve (CLPHP), also called open end PHP (OEPHP); (b) CLPHP with check valves; (c) open loop PHP (OLPHP), also called closed end PHP (CEPHP),see Fig 2.

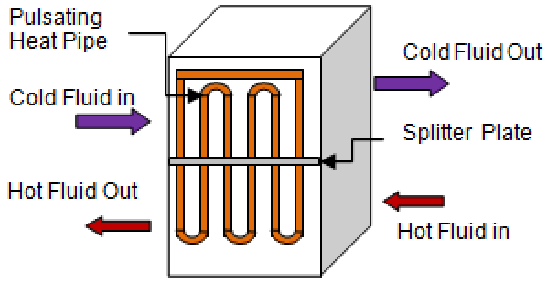

Fig. 1: Heat pipe heat exchanger

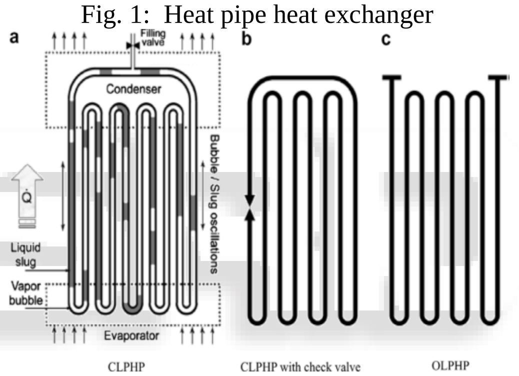

Fig. 2: Schematic of PHPs: (a) CLPHP; (b) CLPHP with check valve; (c) OLPHP [1]

It is well known that there are various limitations of the performance of heat pipes , e.g. capillary limit, boiling limit, entrainment limit, sonic limit, viscous limit. With regard to cooling electronic devices, the capillary and boiling limits are in general the most important ones. In both cases the limit will manifest itself by an unacceptable overheating of the evaporator due to lack of cooling working fluid (dry-out, burn-out).

CLPHP's are capillary tube whose ends are join together and partially filled with working fluid. It form three sections evaporator section where heat is received by the working fluid, condenser section where heat is rejected by the working fluid to the cooling medium and adiabatic section where there is no heat transfer takes place.

While quite some research has been performed on the operational behavior and physical phenomena in PHPs, including various experimental studies and attempts of mathematical modeling rather limited knowledge exists on the ultimate performance or performance limits of PHPs Owing to their wickless structure, PHPs will not be subjected to the capillary limit, though the boiling limit might occur. Miyazaki and Akachi experimentally studied a CLPHP with check valves, which comprised of a total of 28 copper tubes with 2 mm ID. The working fluid was R134a and the filling ratio was approximately 50%. The set-up could operate in all heat modes. They confirmed the existence of dry-out due to insufficient amplitude of oscillatory flow and demonstrated that the installation of check valves is an effective countermeasure to this problem. Maezawa et al. tested an OLPHP, which comprised of a total of 40 copper tubes with 1 mm ID. The working fluid was R142b and the filling ratio was varied among 30%, 50% and 70%. Their set-up could operate both in the bottom and horizontal heat modes, but could not operate in the top heat mode. They found that the OLPHP with 50% filling ratio showed a better thermal performance and a higher performance limit, while the OLPHP with 30% and 70% filling ratios experienced a dry-out at lower thermal performances. Katpradit et al. performed a visual study on two OLPHPs, which consisted of 10 Pyrex glass tubes with inner diameters of 1 mm and 2 mm, respectively. R123 was used as the working fluid with a filling ratio of 50%. Their set-up could only operate in the bottom heat mode. Various flow patterns and their transitions were observed, such as slug flow, churn flow and annular flow. They concluded that the major cause of dry-out was flooding at the entrance of the evaporator section. In the OLPHP with the smaller inner diameter, flooding occurs in annular flow resulting in a lower performance limit, while in the OLPHP with the bigger ID, the flow pattern changed from annular flow to churn flow, causing a higher performance limit. In a recent paper, Katpradit et al. presented two correlations based on experimental data of OLPHPs having 5, 10 and 15 turns of copper tubes with 2.03, 1.06 and 0.66 mm ID, respectively. The working fluids were R123, ethanol and water with a filling ratio of 50%.

As above mentioned, there are only few studies considering performance limits of PHPs. This is especially true for CLPHPs without check valve, which have been confirmed to be more advantageous than OLPHPs and CLPHPs with check valves . Therefore the present paper is mainly focused on the performance limit of CLPHPs without check valve.

II. LITERATURE REVIEW

In 2002, Yang et al. [2] used the HPHE to heat the hull of vehicle in cold area, it will comfort passengers if the heat of automobile exhaust gas is conveyed into the bus carriage utilizing heat pipes. The schematic diagram is shown in figure 3.

Air from carriage to be heated is introduced into a heat pipe heat exchanger by a fan and warmed by the heat from the exhaust gas there from. Then the air flows into carriage to keep comfortable temperature

- It is valuable that using HPHE in heating using exhaust gas.
- For adoption of naked pipe, the pressure drop of exhaust gas is little. The specific data of this project is about 24.4 Pa under normal work condition, which indicates the effect heat exchanger imposes on the engine is tiny. This is a notable advantage of heat pipe heat exchangers over conventional ones.
- Heat transferred by the heat exchanger will increase with the rise of gas temperature.

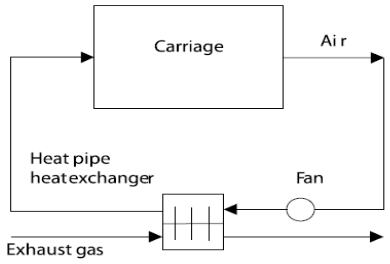

Fig. 3: Schematic diagram of heating system [2]

In 2006, Meyer et al.[3] used the HPHE for recovery of waste heat from a relatively small commercially available air dryer and small to use this heat to preheat the incoming cold air.

The experimental set-up consisted of the HPHE retrofitted to a standard drier using flexible ducting as shown in Figures 4 and 5. For the drier, its overall dimensions are 2.8 m long, 1.4 m wide and 1.9 m high. The overall dimensions of the HPHE are shown in Figure 5 and it was manufactured in accordance with standards and technology for copper pipe and aluminum plate finned heat exchangers as normally applied in the HVAC industry. The air-drier typically evaporates water from the product being dried and exhausts this moist warm air into the atmosphere. With the HPHE installed, this warm moist air is then fed through the evaporator section of the HPHE. Fresh ambient air is then drawn through the condenser section of the HPHE, where it is heated up and is then fed back into the system thereby reducing the load on the heating elements inside the drier.

Temperature measurements were taken at the inlets and outlet of the respective hot and cold streams, and an anemometer was used to measure the flow velocities, from which the air mass flow rates could be calculated. A kWh-meter was used to measure the electrical energy consumption. To ensure accuracy and repeatable drying operations, the product to be dried was simulated using wet towels laid out on the drying racks. Tests runs with and without the HPHE could thus be compared.

The heat transfer rate between the hot and cold streams of the heat pipe (thermosyphon) heat recovery heat exchanger is accurately predicted by the theoretical model for average temperature difference between the two streams of greater than 15°C.

The experimental evaluation of the heat recovery heat exchanger retrofitted to the mini-drier yielded a 32% saving of R2 321 per annum a significantly lower payback period is deemed possible if the heat exchanger be included in the design of the mini-drier as a standard production feature.

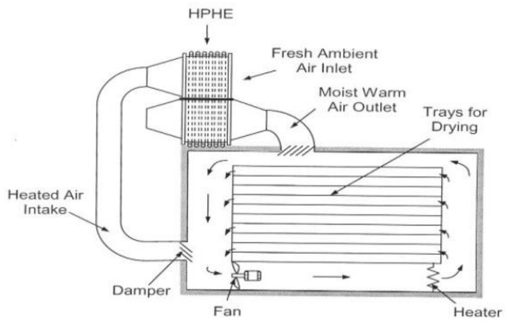

Fig. 4: Schematic diagram of the HPHE retrofitted to the mini-drier. [3]

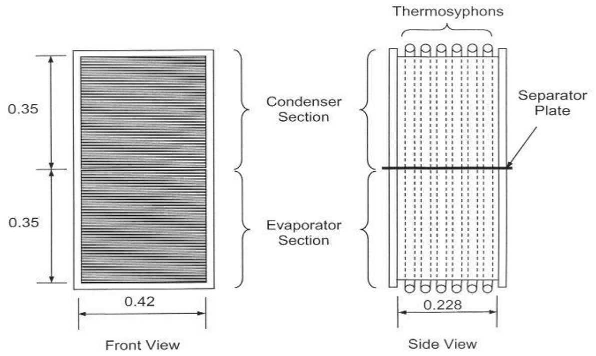

Fig. 5: The as-designed and manufactured HPHE [3]

In 2007, Hagens et al. [5] presented measurements and predictions of a heat pipe equipped heat exchanger with two filling ratios of R-134a 19% and 59%. The length of the heat pipe is long (1.5m) as compared to its diameter (16mm). The air flow rate varied from 0.4 to 2.0 Kg/s. the temperatures at the evaporator side of the heat pipe of the heat pipe varied from 40 to 70^{o}C and at the condenser part from 20 to 50^{o}C. The measured performance of the heat pipe has been compared with predictions of two pool boiling models and two filmwise condensation models.

It is found that a heat pipe equipped heat exchanger can replace a water- cooled heat exchanger without loss of performance. The tested process conditions are typical for warmer countries like Bahrain. This study therefore demonstrates that it is possible to apply heat pipe based cooling equipment in practical conditions of warmer countries.

In 2009, Nuntaphan et al. [6]performed experiment on wire on tube heat exchanger of which the wire is a oscillating heat pipe. The experiments for this heat exchanger were performed in a wind tunnel by exchanging heat between hot water flowing inside the heat exchanger tubes and air stream flowing across the external surface. R123, methanol and acetone were selected as working fluids of the oscillating heat pipe. The inlet water temperature was varied from 45 to 85^{o}C while the inlet air temperature was kept constant at 25^{o}C.

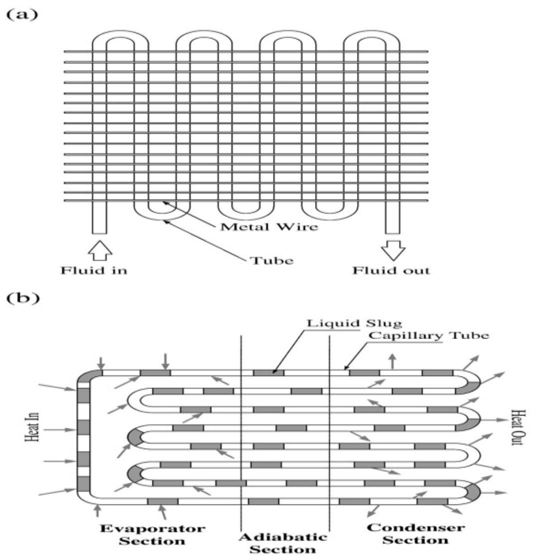

Fig. 6: Wire-on-tube heat exchanger and closed-loop oscillating heat pipe. [7]

It is observed that the heat transfer rate of wire on tube heat exchanger can be enhanced by using an oscillating heat pipe. The heat transfer rate is increased around 10% when the inlet temperature of water is between 60- 80^{o}C. the performances when using R123, methanol and acetone are nearly the same.

In 2010, Hemadri et al.[7] performed experiment of embedded PHP thermal radiators having two different effective Biot numbers respectively and subjected to conjugate heat transfer conditions on their surface i.e. natural convection and radiation , has been carried out under different thermomechanical conditions. High resolution infrared camera is used to obtain spatial temperature profiles of the radiators. To complete the experimental study , detailed 3D computational heat transfer simulation has also been undertaken by embedding PHP structures, it was possible to make the net thermal resistance of the mild steel radiator plate equivalent to aluminium radiator plate in spite of large difference in their respective thermal conductivities ($K_{al} = 4 K_{ms}$).

In these situations where external heat transfer coefficient limits the net heat throughput, the thermal conductivity of the base plate on which the heat pipe is embedded does not play a major role in improving the overall heat transfer scenario, after a particular minimum value of its effective thermal conductivity is attained.

The effect of orientation of the plate on its thermal performance was also studied. The operating inclination angle of the PHP tubes affects overall heat transfer characteristics. These changes can be attributed to the change in internal flow patterns and pulsating action.

In order of magnitude of effective thermal conductivity achievable by PHP ranges from 400W/mK – 2300 W/mK, depending on the heat flux applied, increasing with increasing applied heat flux. These values are sufficiently attractive for its use as embedded structures in thermal radiator systems.

In 2011, Timea et al. [8] used heat pipe heat exchanger to recover energy from waste water. Figure 7 shows the schematic diagram of the experimental apparatus. The system is composed of three major parts: water heater (for wastewater preparation), heat pipe heat exchanger and devices for measurement and control of parameters. In the installation there are two circulating fluids: the hot agent (wastewater) in the lower chamber of the heat exchanger and the cold agent (cold water) in the upper chamber of the heat exchanger.

The heat pipe heat exchanger was equipped with 40 heat pipes arranged vertically at an angle of 90 ° . A heat pipe has a length of 1390 mm, 16 mm external diameter and wall thickness of 1 mm. The working fluid used in heat pipe has a filling ratio of 20%.

The input and output temperature, the flow of thermal agents and running time were measured in this experimental research. Determination of efficiency of heat recovery was achieved under the following conditions: wastewater temperature equal to 30 °C, different flow rates: 0.5 m^3/h, 0.4 m^3/h and 0.3 m^3/h, the flow and temperature of cold water from network was constant (0.15 m^3/h and 17°C). Measurements were made of 5 in 5 minutes, the operation of the heat pipe heat exchanger was 80 minutes.

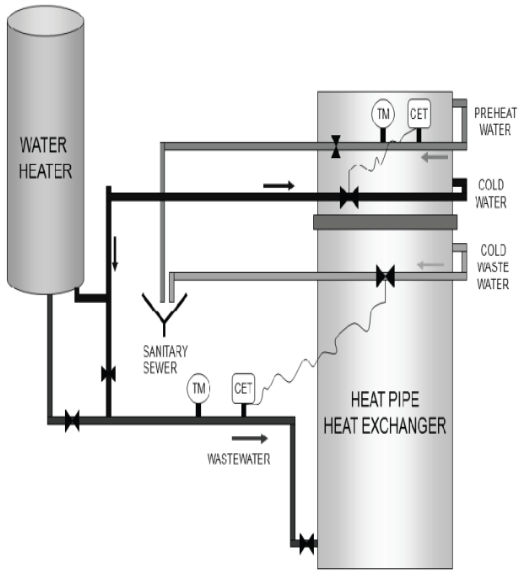

Fig. 7: Schematic diagram of the experimental apparatus [8]

It is found that, the recovery of residual heat from municipal wastewater depends on their flow rates. The higher the flow rate greater the recovered temperature gets. The efficiency of the heat exchanger depends very much on the preheated cold water flow rate. The cold water flow rate must be closed to the flow rate of waste water. The operating time influences the entire recovery process. From measurements made it can be observed that after 65- 70 minutes the system has started to enter a steady state regimen, the temperature difference being slightly increased.

III. Conclusion

A short review of heat pipe contains mainly data from application as heat exchanger which testifies that heat pipes are very efficient heat transfer devices, which can be easily implemented as thermal links and heat exchangers in different systems to ensure the energy saving and environmental protection.

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