Thermodynamic Performance Evaluation of Heat Pipe

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Abstract
Heat pipe is known as one of the most energy efficient passive heat transfer device with high thermal conductivity. In the present paper, the thermodynamic performance of heat pipe is experimentally evaluated at different operational angles with different mass flow rates of external cooling water at condensing section. It is found that the heat transfer rate is maximum (i.e. 754 W) at the heat pipe orientation of 30°.

1. Introduction

Heat pipe was invented by Gaugler [1], but it was Grover [2] who coined the term "Heat Pipe" and described it "as synergistic engineering structure having very high thermal conductance exceeding that of any known material." It is a sealed device which transfers heat from one end (evaporator) to another end (condenser), passively. Gaugler [1], who was working on refrigeration problems at that time, envisioned a device which would evaporate a liquid at a point above the place where condensation would occur without requiring any additional work to move the liquid to the higher elevation. His device consisted of a closed tube in which the liquid would absorb heat at one location causing the liquid to evaporate. The vapor would then travel down the length of the tube, where it would recondense and release its latent heat. It would then travel back up the tube via capillary pressure to start the process over.

Grover et al. [3] and Grover [2] built several prototype heat pipes, the first of which used water as a working fluid, and was soon followed by a sodium heat pipe which operated at 1100 K. The recognition of the heat pipe as a reliable thermal device was initially due to the preliminary theoretical results and design tools that were reported in the first publication on heat pipe analysis by Cotter [4]. Lee et al. [5] analyzed a vertical air-to-air HPHE with heat pipes as water - copper thermosyphons. Peretz et al. [6] studied the optimization of HPHE for waste heat recovery for achieving maximum energy saving. Azad et al. [7] presented a theoretical approach for the design of GAHPHE for a solar agricultural dryer to recover the heat from the waste exhaust moist air at about 70°C.

In continuation of earlier work on GAHPHE, Azad et al. [8] presented the design study on GAHPHE. In this study gravity assisted HPs were used for water to air heat exchanger to convert thermal energy of hot water from a solar collector to heat the cold air entering into the dryer. Azad et al. [9] presented the theoretical analysis of co-axial HPHE and effectiveness-NTU approach was used to deduce the heat transfer characteristics. In this work like Azad's previous works air to water heat exchanger was studied but in this work finned co-axial heat pipes as the heat transfer element and water was used as working fluid. Azad et al. [10] presented the theoretical frame work for predicting the thermal performance of circular finned based heat pipe heat recovery system. Effectiveness-NTU approach was used and row by row heat transfer calculations were performed. Stulc et al. [11] used an iterative marching method to model the vertical thermosyphon based HPHE for HVAC application. Inlet temperatures were assumed for each fluid stream.

From an energy balance across each heat pipe row of the heat exchanger, the temperature rise of the low-temperature fluid and temperature drop of the high-temperature fluid across each row were determined and by the cascading procedure, the total temperature increase of the low-temperature fluid and drop of the high-temperature fluid across the entire heat exchanger were determined. Tan and Liu [12] analyzed the air-to-air straight HPHE using the effectiveness- NTU approach for energy recovery application. Yau and Tucker [13] simulated the overall effectiveness of a wet 6-row wickless HPHE (thermosyphon type) in a tropical building's HVAC system. Noie [14] investigated the thermal performance of thermosyphon based air to air heat exchanger for heat recovery from the exhaust gases for an industrial plant. Yau [15] claimed that the impact of condensate layer forming on the fins of HPHE, on the performance of a thermosyphon based HPHE operating in high humid conditions was negligible. Wan et al. [16] examined the effect of a loop heat pipe air handling unit on the energy consumption of a central air conditioning system for an office building. Yau [17] simulated the use of double HPHE for reducing the energy consumption of treating ventilation air of an operating theatre located in the tropical climate.

The advantage of using a heat pipe over other conventional methods is that large quantities of heat can be transported through a small cross sectional area over a considerable distance with no additional power input to the system. Furthermore, design and manufacturing simplicity, small end-to-end temperature drops, and the ability to control and transport high heat rates at various temperature levels are all unique features of heat pipes. Heat pipe has no moving parts, require no external energy, and is reversible in operation and completely silent. Heat pipes can be designed to operate over a very broad range of temperatures from cryogenic (< -243°C) applications utilizing titanium alloy/nitrogen heat pipes, to high temperature applications (>2000°C) using tungsten/silver heat pipes [18-19].

There are five primary heat pipe heat transport limitations. These heat transport limits, which are a function of the heat pipe operating temperature, include: viscous, sonic, capillary pumping, entrainment or flooding, and boiling [20].

2. Thermodynamic analysis of heat pipe

2.1 Working of heat pipe

Figure 1 shows the T-S diagram for a heat pipe. The process can be summarized as-

2.1.1Process (1-2): Evaporator section is given heat from external source. Heat applied vaporizes the working fluid to a saturated (2') or superheated (2) vapor.

2.1.2 Process (2-3): High vapor pressure and temperature develops at the evaporator side. Vapor under high pressure moves from evaporator side to condenser side passing through adiabatic section.

2.1.3 Process (3-4): Vapor releases its heat at the condenser side. And changes it phase to liquid.

2.1.4 Process (4-1): This condensate returns back to the evaporator end because capillary action presented by a wick structure, which is wrinkled on the within the heat pipe container. Cycle starts over [21].

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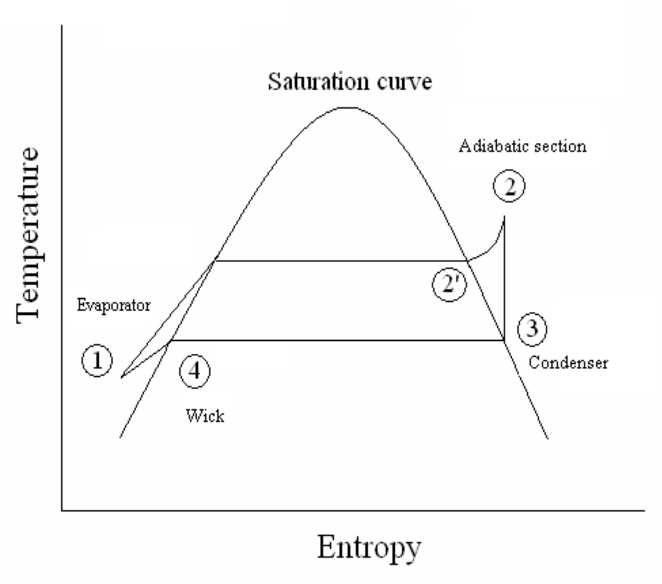

Fig.1: T-S diagram for a heat pipe [21]

The wick has a limited thermal resistance, due to heated evaporator section. A pressure difference develops between evaporator and condenser section. Evaporator side reaches higher pressure and temperature. The wick in this case serves as "thermal lock". The interfacial forces inside the saturated wick which holds the liquid in it. Prevent high pressure vapours from penetrating the wick material. The interface will hold the pressure, preventing any back flow and at the same time providing uninterrupted liquid flow. Thus, another function of the wick is that of hydraulic lock [22-23]. Figure 2 shows a loop heat pipe system containing all the sections.

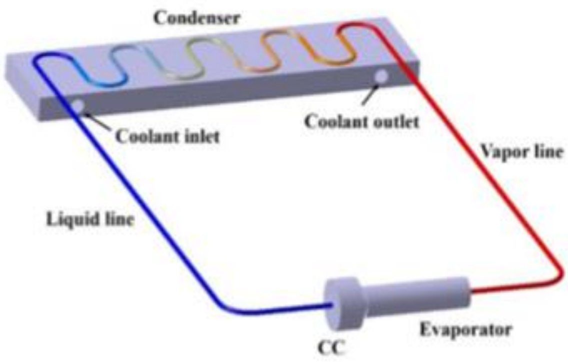

Fig.2: Loop heat pipe system

2.2 Thermodynamic model

At the evaporator section, heat given is used to evaporate the liquid refrigerant. Major part of the heat given is absorbed by the liquid ($Q_{e,v}$). Some part of Q_e is used to raise the temperature of the compensation chamber ($Q_{e,cc}$). This heat has been conducted across the wick.

$$Q_e = Q_{e,v} + Q_{e,cc} \quad (1)$$

The condenser section is divided into 3 regions. Superheated vapour, two-phase flow region and sub cooled liquid. At the condenser section, the vapours at high temperatures release their heat to surroundings or the cooling medium used. Heat released can be calculated using the Equation 2.

$$Q_C = m \times C_p \times (\Delta T) \quad (2)$$

2.3 Assumptions

The purpose of making assumptions is to reduce the number of variables. This simplifies the problem. Following are some reasonable assumptions made in the analysis of heat pipe [23-24].

1. A piecewise steady state thermal model is taken along the heat pipe.
2. The compensation chamber is at saturated mixture equilibrium conditions.
3. The liquid is leaving the compensation chamber as a single-phase liquid.
4. The phase change occurs at a constant temperature and pressure.
5. Wick is fully wetted with liquid.
6. The vapor and liquid lines and the compensation chamber are insulated and have single phase flow.
7. The flow is laminar.
8. Incompressible flow is assumed.

3. Experimental set-up

3.1 Objectives and investigations of present work

Design and development of test rig to evaluate performance of heat pipe installed in different orientations namely: Inclined orientation, Horizontal orientation, Vertical orientation. To find: heat transfer rate and effectiveness of heat pipe. The trial is conducted on the heat pipe system to determine the temperature difference at hot water outlet and cold water inlet for three orientations i.e. inclined orientation, horizontal orientation, and vertical orientation. The design guide of a heat pipe to fulfil a partial duty involves four broad processes:

- Selection of appropriate type and geometry
- Selection of candidate materials
- Evaluation of performance limits
- Evaluation of actual performance

As with any design process, many of the decisions that must be taken are interrelated and the process is iterative .For example, choice of the wick and case material eliminates many candidate working fluids (often including water) due to compatibility constraints. If the design then proves inadequate with the available fluids, it is necessary to reconsider the choice of construction materials.

3.2 Experimental set-up description

Figure 3 shows the experimental set-up of heat pipe. The design of heat pipe test rig consists of following components:

3.2.1 Structural frame (body): Mild steel (1/2" rectangular cross section) is selected as the material for the frame of test rig because of the following benefits: Cost factor is of prime importance as other steel are more costly than Mild steel. This grade of steel does not harden when heated and chilled with cold water, so further machining can be easy. It is easily available and has high strength and high toughness.

3.2.2 One heat pipe: A Copper heat pipe of 500 mm length and 16 mm diameter is selected. The wick material is wire mesh and the refrigerant used is distilled water (boiling point 100°C). It is placed on the transverse member of the frame with the help of clamps and can be oriented in different angular positions with the help of swivel pins in the frame.

3.2.3 One band heater: An electrical heat source for circular cross sections (here heat pipe). The diameter and the length of band heater used are 16 mm and 25.4 mm respectively.

3.2.4 Water storage tank: Tank is provided to store water which is used as a heat sink in the water jacket placed at condenser side of heat pipe and another tank of known cross section to collect hot water in order to measure discharge.

3.2.5 A pump and a flow control valve: A pump is required to provide the required head depending upon the position of water jacket and a flow control valve is required to vary the discharge so that heat transfer rate at different discharges can be calculated.

3.3. Process data to heat pipe

Mass flow rate of cooling water, $m = \frac{l \times b \times h}{t}$ (3)

where, l = length of the tank
b = breadth of the tank
h = height up to which water was filled

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t = time taken to fill the storage tank up to height h

Area of tank, $A = l \times b = 333.5\ cm^2$ (4)

Heat dissipation, $Q_C = m \times c_p \times (\Delta T)$ (5)

Fig.3: Heat pipe test rig

4. Results and discussion

The experiments are carried out at different orientations of heat pipe. The heat is supplied to evaporator section with the help of band heater. At a particular orientation, the mass flow rate of cooling water at condensing section is varied with the help of variable speed pump. The experimental results obtained for different orientation of heat pipe are tabulated from Table 1 to 4.

Table 1 Results at horizontal position (0°)

Time (t) [s]	Height of tank (h) [cm]	Temperature difference (ΔT) [°K]	Mass flow rate (m) [kg/s]	Heat dissipation (Q_C) [J/s]
25	4.5	3.0	0.0603	757.42
25	6.2	1.5	0.07696	483.34
20	4.8	1.0	0.08004	335.12

Table 2 Results at horizontal position (30°)

Time (t) [s]	Height of tank (h) [cm]	Temperature difference (ΔT) [°K]	Mass flow rate (m) [kg/s]	Heat dissipation (Q_C) [J/s]
63	5.5	6.4	0.02911	780.05
25	6.2	2.0	0.08270	692.52
29	6.1	3.3	0.07015	969.26

Table 3 Results at horizontal position (60°)

Time (t) [s]	Height of tank (h) [cm]	Temperature difference (ΔT) [°K]	Mass flow rate (m) [kg/s]	Heat dissipation (Q_C) [J/s]
22.5	5.2	2.1	0.07707	677.65
23	5.3	1.4	0.07685	450.48
21	4.3	0.9	0.06828	257.33

Table 4 Results at horizontal position (90°)

Time (t) [s]	Height of tank (h) [cm]	Temperature difference (ΔT) [°K]	Mass flow rate (m) [kg/s]	Heat dissipation (Q_C) [J/s]
37	3.5	2.1	0.03154	277.32
23.7	4.8	0.9	0.06754	254.51
25	5.0	0.7	0.0667	195.49

Figure 4 shows the variation of temperature difference between water outlet temperature and water inlet temperature with mass flow rate for heat pipe in different orientations. It is noticed that the temperature difference for heat pipe in inclined orientation of 30° is greater as compared to temperature difference for heat pipe in inclined (60°), vertical (90°) and horizontal (0°) orientation. It can be observed from Figure 4 that the temperature difference for heat pipe in inclined orientation of 30 ° is 6.4°C and respective mass flow rate is 0.02911 kg/sec. Temperature difference (0.7°C) which is minimum for the mass flow rate of 0.667 kg/sec in vertical orientation i.e. 90°.

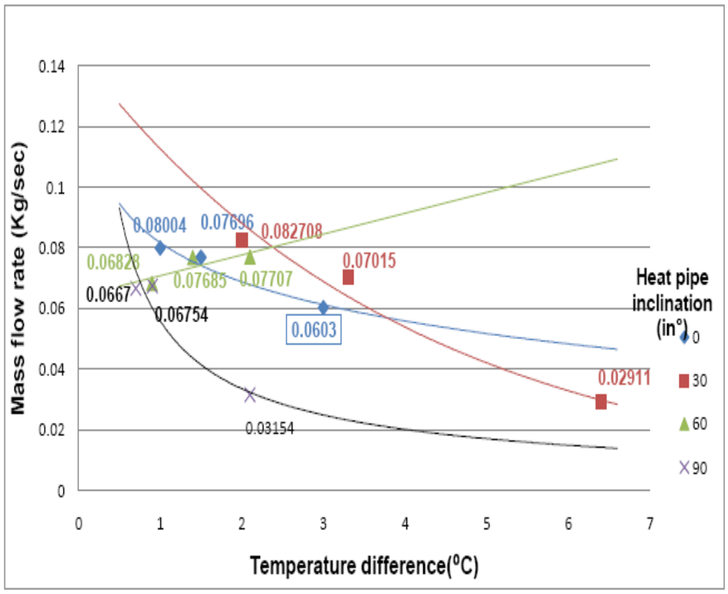

Fig.4: Variation of mass flow rate of external cooling water with temperature difference

Figure 5 shows the variation of temperature difference with heat transfer rate for heat pipe in different orientations. It is noticed from the figure that the heat transfer rate for heat pipe in inclined orientation of 30° is greater as compared to heat transfer rate heat pipe in inclined (60°), vertical (90°) and horizontal (0°) orientation. From the Figure 5, it can be observed that the heat transfer rate for heat pipe in horizontal orientation is 754 watt at temperature difference of 3°C, for heat pipe in vertical orientation heat transfer rate is 277.38 watt at temperature difference of 2.1°C, for heat pipe in inclined orientation

(30°) the heat transfer rate is 780 watt at temperature difference of 6.4°C.

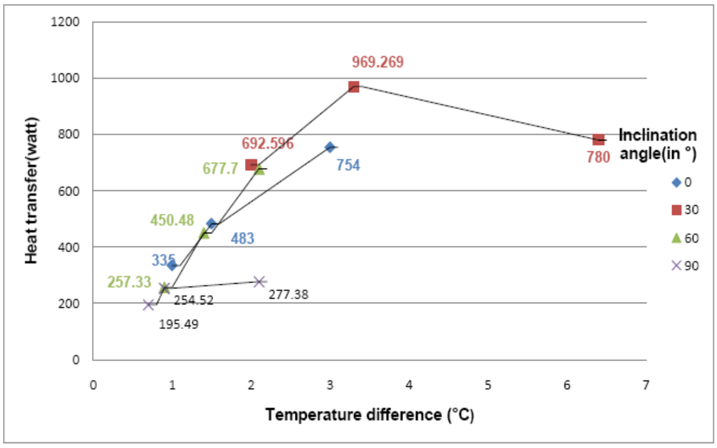

Fig. 5: Variation of heat rejected in condensing section with temperature difference

5. Conclusions

In the present paper, the thermodynamic performance of heat pipe is evaluated at different orientations. The paper also reports the effect of mass flow rate of cooling fluid on the performance of heat pipe. It can be observed from the results that the heat transfer is maximum (i.e. 754 W) at an orientation of 30°. It can be concluded from the present study that heat pipe technology offers a very efficient solution for the thermal cooling problems of the high density and high speed electronic and mechanical system. The above study is useful for further design and development of heat pipe technology for further refrigeration and air-conditioning applications.

Nomenclature

A	cross sectional area of tank (m^2)
b	breadth of tank (m)
c_p	specific heat at constant pressure (J/kg-K)
h	height of tank (m)
l	length of tank (m)
m	mass flow rate of cooling water (kg/s)
Q_C	heat rejected in condensing section (W)
Q_e	heat supplied in evaporative section (W)
t	time (s)
ΔT	temperature difference (K)

References

[1]. R Gaugler. Heat transfer device, US2350348 A, 1944.
[2]. G. Grover. Evaporation-condensation heat transfer device, US 3229759 A, 1966.
[3]. G Grover, T Cotter, G Erickson. Erratum: Structures of Very High Thermal Conductance, Journal of Applied Physics, 35(10), 1964, 3072-3072.
[4]. T Cotter. Theory of heat pipes. Los Alamos, N.M.: Los Alamos Scientific Laboratory of the University of California, 1965.
[5]. Ylee, A Bedrossian. The characteristics of heat exchangers using heat pipes or thermosyphons. International Journal of Heat and Mass Transfer, 21(2), 1978, 221-229.
[6]. R Peretz, B Horbaniuc. Optimal heat pipe heat exchanger design", Journal of Heat Recovery Systems, 4(1), 1984, 9-24.
[7]. E Azad, F Geoola. A design procedure for gravity-assisted heat pipe heat exchanger. Journal of Heat Recovery Systems, 4(2), 1984, 101-111.
[8]. E Azad, F Bahar, F Moztarzadeh. Design of water-to-air gravity-assisted heat pipe heat exchanger. Journal of Heat Recovery Systems, 5(2), 1985, 89-99.
[9]. E Azad, F Moztarzadeh. Design of air-to-water co-axial heat pipe heat exchanger. Journal of Heat Recovery Systems, 5(3),1985, 217-224.
[10]. E Azad, F Mohammadieh, F Moztarzadeh. Thermal performance of heat pipe heat recovery system. Journal of Heat Recovery Systems, 5(6), 1985, 561-570.
[11]. P Stulc, L Vasiliev, V Kiseljev, J Matvejev. Heat pipe heat exchangers in heat recovery systems. Journal of Heat Recovery Systems, 5(5), 1985, 415-418.
[12]. J Tan, C Liu. Predicting the performance of a heat-pipe heat exchanger, using the effectiveness- NTU method. International Journal of Heat and Fluid Flow, 11(4), 1990, 376-379.
[13]. Y Yau, A Tucker. The performance study of a wet six-row heat-pipe heat exchanger operating in tropical buildings. International Journal of Energy Research, 27(3), 2003, 187-202.
[14]. S Noie. Investigation of thermal performance of an air-to-air thermosyphon heat exchanger using ε-NTU method. Applied Thermal Engineering, 26(5-6), 2006, 559-567.
[15]. Y Yau. Experimental thermal performance study of an inclined heat pipe heat exchanger operating in high humid tropical HVAC systems. International Journal of Refrigeration, 30(7), 2007, 1143-1152.
[16]. J Wan, J Zhang, W Zhang. The effect of heat-pipe air-handling coil on energy consumption in central air-conditioning system, Energy and Buildings, 39(9), 2007, 1035-1040.
[17]. Y Yau. The use of a double heat pipe heat exchanger system for reducing energy consumption of treating ventilation air in an operating theatre—A full year energy consumption model simulation. Energy and Buildings, 40(5), 2008, 917-925.
[18]. Mustafa. Study of Heat Pipe. Slideshare.net, 2017. https://www.slideshare.net/shefinmustafa/study-of-heat-pipe.
[19]. Advantages of using Heat Pipes for Energy Recovery. | DAC SALES, Dac-hvac.com, 2017. http://www.dac-hvac.com/energy-recovery-heat-pipes-5-advantages-of-using-heat-pipes-for-air-to-air-energy-recovery/.
[20]. D Reay, P Kew, R McGlen. Design guide. Heat Pipes, 2014, 95-104.
[21]. Faghri, Amin. Heat Pipe Science and Technology. US: Taylor & Francis 1995.
[22]. S Launay, V Sartre, J Bonjour. Parametric analysis of loop heat pipe operation: a literature review, International Journal of Thermal Sciences, 46(7), 2007, 621-636.
[23]. http://altmine.mie.uc.edu/fgerner/public_html/lhp3.pdf
[24]. M Hamdan, E Elnajjar. Thermodynamic analytical model of a loop heat pipe. Heat and Mass Transfer, 46(2), 2009, 167-173.