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Experimental Investigation of Flat Heat Pipe for Cooling System Using Cross-flow Heat Exchanger

(Penyelidikan Eksperimen Ke Atas Paip Haba Rata Untuk Sistem Penyejukan Menggunakan Penukar Haba Aliran Silang)

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Abstract

Nowadays, advanced technology that has been introduced is beneficial in every aspect of human life. Despite the advantages, the technology also brings some disadvantages, especially to the environment, for example, high heat dissipation due to the increase in operating wattage and power. Thus, a study on heat management is necessary to provide a better cooling system to sustain the performance of the technology. The purpose of this experiment is to fabricate a flat heat pipe to investigate the cooling effect when R-134a is used as the working fluid powered by 750W of a resistance heater. The heat pipe comprises a copper container that is sealed and contains a working fluid, along with a heat exchanger. It can be divided into three distinct sections: the evaporator section, the adiabatic section, and the condenser section. The flat heat pipe is a part where it receives the heat and lets the evaporation process take place while the heat exchanger is where the condensation process occurs. Meanwhile, in the adiabatic section, a crossflow heat exchanger is designed so that two fluids flow perpendicular to one another. The operating pressure inside the heat pipe is vacuum pressure to make the boiling temperature of working fluid occur at a lower temperature. The heat pipe was studied experimentally using Refrigerant 134a compared to water as the working fluids and tested with three different pressures. Water is also used as a cooling medium to transport thermal energy. From the experiment, the data are collected from six points attached to the heat pipe. At the end of the study, results of different temperatures between two endpoints of the heat exchanger are collected to determine the heat transfer efficiency. The efficiency of thermal energy is then compared with the same experimental study but using different designs of heat exchangers.

Keywords: Cooling system, Flat heat pipe, Heat exchanger, Working fluids.

INTRODUCTION

The study of heat transport stands as a vital pursuit within the realm of thermal engineering. Despite numerous costly endeavours aimed at enhancing heat transportation efficiencies, cooling systems have remained stagnant. As a result of this predicament, overheating issues persist as a prevalent cause of system failures. To address this challenge, thermal engineering has embraced a practical solution in the form of heat pipes, which offer a promising avenue towards achieving improved cooling systems.

Given the prevailing global energy crisis, there has been a significant increase in research efforts directed towards energy conservation. Particularly, the thermal management of electronic and electrical components, known for their compact sizes and powerful capabilities, has garnered attention. These components generate substantial amounts of heat, prompting the utilization of heat pipes for effective heat transfer over considerable distances owing to their highly effective thermal conductivity (Paisan, 2010).

Heat pipes find wide-ranging applications, with a primary focus on the electronic industry. The damaging effects of excessive heat on electronic devices, notably the central processing unit (CPU) in computer systems, have been witnessed globally. Furthermore, heat pipes play a vital role in spacecraft for managing internal temperature conditions, as well as in pipelines and passive cooling systems, effectively alleviating air-conditioning loads. This underscores the importance of heat pipes in ensuring efficient conventional cooling systems without the need for moving parts. Consequently, further research is essential to enhance heat transportation efficiency through the utilization of heat pipes.

Therefore, the primary objective of this study is to investigate the design of a constructed flat heat pipe that is filled with different pressures of Refrigerant 134a (R-134a) and water as working fluids. By conducting this research, we aim to advance our understanding and optimize the efficiency of heat transportation using heat pipes.

Regarding the working fluid selection, water was chosen for this project due to its high latent heat, which reduces the inventory requirement and cost. Additionally, water exhibits a high "figure of merit" and compatibility with various container materials, with copper being the most popular choice. On the other hand, R-134a serves as a novel alternative to water, offering improved efficiencies. It was selected based on its low toxicity compared to other refrigerants and its non-ozone-depleting nature, contributing to the reduction of global warming effects.

LITERATURE REVIEW

The flat heat pipe has recently garnered substantial attention for its remarkable ability to dissipate heat in a localized manner. Previous studies predominantly emphasize its application in cooling electronic devices, highlighting the increasing need for effective heat management. This necessity arises from the continuous advancements in electronic component performance, resulting in higher operating wattage requirements. Therefore, with the escalating heat generation, proper heat dissipation management becomes imperative to optimize the system. Bar-Cohen (1983), as cited by Yeh and Chu (2002), highlighted that the reliability of electronic components diminishes by 10% with every 2°C increase above the normal operating temperature. When the operating temperature of a chip exceeds acceptable limits, it adversely affects the performance and stability of electronic components, potentially resulting in system or product failure. Therefore, it becomes imperative to effectively dissipate the heat generated by electronic equipment to maintain consistent performance.

Amollo et al. (2013) in their research found that computers dissipate a lot of heat and increase the processor workload resulting in high conductive absorbance with heat sinks and then convection of the heat to air or water. According to Sergei (2010), as cited by

Amollo, the amount of heat generated by a computer is influenced by various factors including the type and speed of the CPU, the type, size, and efficiency of the CPU cooler, the cleanliness of the CPU cooler, the number of PC cards installed, the type of PC cards used, the case design, the number and type of case fans installed, the CPU's running processes, the make of the graphic cards, and the motherboard design. Maintaining the CPU's operating temperature below a specific threshold is crucial for ensuring the reliability of a personal computer (PC), as highlighted by Belhardj (2003).

Flat heat pipes are becoming increasingly popular for cooling electronics due to their high reliability and efficient energy transport capabilities. Among the various types, the flat plate unit is particularly valuable in electronics cooling. It is commonly utilized for heat spreading or temperature flattening purposes and excels in these applications. Heat spreading involves the equalization of temperatures from multiple heat sources or the effective transfer of heat from heat sources to heat sinks. In a study conducted by Sonan et al. (2008) on the cooling of electronic components, a flat heat pipe was utilized as a spreader to cool multiple electronic components. The study involved analyzing the performance of the flat heat pipe (FHP) when subjected to heating from multiple electronic components during a transient period. The findings demonstrate that the FHP effectively functions as a thermal spreader, resulting in a more even distribution of temperature compared to a solid plate. Furthermore, the calculated pressure drops in both phases indicate that the heat pipe operates within the appropriate range during the transient stage investigated, without reaching the capillary limit.

In Mehmet Esen's (2004) research on a solar cooking system employing vacuum-tube collectors with heat pipes containing refrigerants R-407C, R-22 and R-134a, it was observed that R-22 and R-134a exhibited superior heat absorption capabilities. Consequently, further analysis specifically focusing on R-134a will be pursued. Presently, there are only a limited number of studies utilizing refrigerant 134a as the working fluid in heat pipes. Although R-134a has been utilized in heat pipes for electronic component cooling, its application has been relatively small in scale. Therefore, it is necessary to explore further initiatives regarding the utilization of R-134a as a working fluid. Additionally, the use of refrigerant 134a can potentially be expanded to other applications of heat pipes, such as temperature warning systems, sensors, cooling units, and more.

Zhang (2001) conducted an experimental study aiming to propose a novel working fluid for certain fluids that exhibit a negative surface-tension gradient, making them unsuitable for effective spreading or rewetting on heated surfaces. The objective of that experiment was to enhance the performance and operational stability of capillary-pumping heat pipe systems. The experiment involved using an aqueous solution of n-heptanol and pure water. The results demonstrated that the surface gradient of n-heptanol becomes positive when the temperature reaches 40°C, provided the concentration exceeds 1×10^{-3} mole per litre. It is noteworthy that only a small amount of long-chain alcohol is required to modify the surface tension characteristics of water while leaving other bulk properties unaffected.

METHODOLOGY

In this study, our goal is to analyze a closed-loop flat heat pipe. Heat pipes transfer heat through the system via the evaporator-condenser process. To ensure optimal performance and minimize the risk of leakage, precise design and fabrication of the container, copper valve, pressure gauge, and copper tube are crucial. The flat heat pipe and tube are specifically constructed using copper due to their excellent thermal conductivity. Accurate measurements are carried out throughout the fabrication process to ensure the desired specifications are met. By carefully designing and manufacturing these components, we can create a flat heat pipe system that operates efficiently and has a minimal probability of leakage occurring. According to Aniruddha et al. (2017), copper has been identified as an ideal material for heat pipes operating within the temperature range of 0°C to 200°C, particularly in applications such as electronics cooling.

In this project, careful consideration was given to the selection of materials and components. The container, which acts as a crucial heat exchanger, was constructed using Perspex due to its lightweight nature and aesthetic appeal, which was further enhanced through meticulous finishing techniques. In terms of practicality, the platform material chosen was lightweight aluminium, enabling easy portability and handling during transportation. This choice ensures that the system can be conveniently moved and utilized in various locations. The flow of fluids within the system was facilitated by PVC pipes, while R-134a and water were chosen as the working fluids. Table 1 provides an overview of the related properties of R-134a and other alternative refrigerants, highlighting the favourable environmental characteristics of R-134a as compared to its counterparts.

Table 1. Properties of R-134a and other refrigerants

Medium	Boiling Point at Atmosphere Pressure (°C)	Ozone Depletion Level	Global Warming Potential (GWP)	Critical Temperature (°C)
R-134a	-26.1	0	1300	122
R-22	−40.7	0.055	1810	96.2
R-410a	−48.5	0	2088	72.8

To optimize heat transfer, a flat heat pipe is typically operated under vacuum conditions. By creating a vacuum environment, the boiling point of the fluid within the heat pipe is lowered, leading to increased efficiency in transferring heat. For practical investigations, R-134a is a commonly employed refrigerant due to its global recognition and extensive use in cooling systems. This makes it a suitable choice for studying the performance of flat heat pipes in various applications.

The data acquisition process involved supplying heat to the heat pipe through a resistance heater and placing six thermocouples at different locations along the pipe. These thermocouples were connected to a Midi Lodger, which accurately recorded the temperature readings. For a visual representation of the experimental setup, Figure 1 displays a schematic diagram and Figure 2 showcases the design of the setup itself.
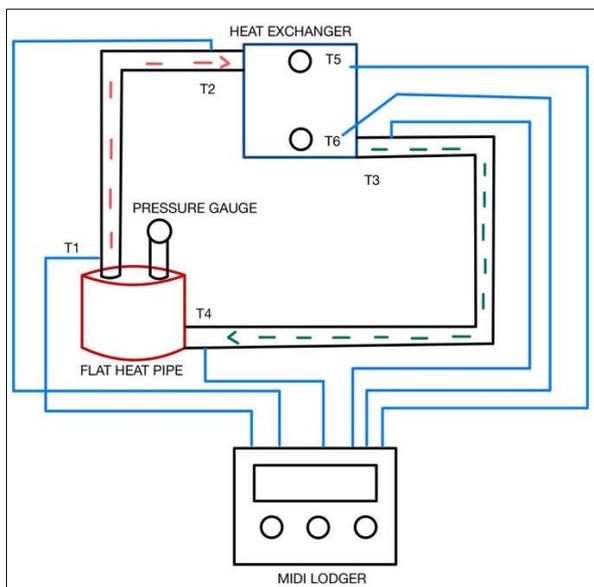

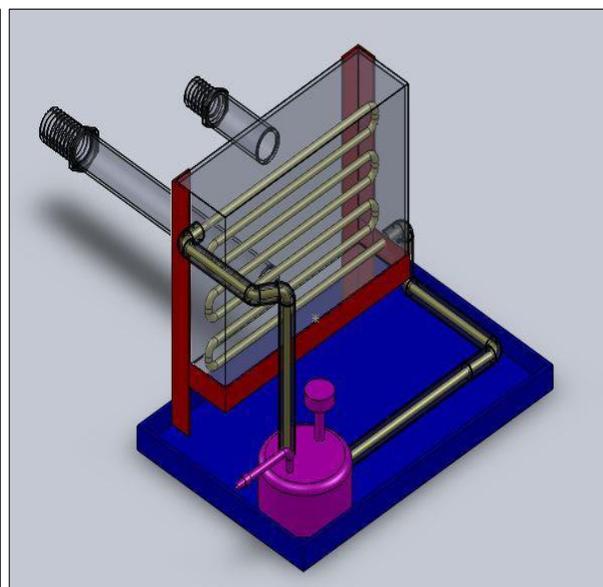Figure 1. Schematic diagram of the heat pipe experimental setup

Figure 2. Design of the heat pipe experimental setup

RESULT AND DISCUSSION

Several tests were conducted on the design to obtain the result. Using a selected model, researchers performed meticulous calculations to identify the ideal pressure and mass flow rate, resulting in maximum heat transfer. Furthermore, the study explored the influence of mass flow rate and pressure on heat transfer rates, using water and R-134a as the working fluids. Additionally, a comparative analysis of heat exchangers with different designs was conducted. The pressure conditions tested encompassed 12psi, 24psi, and 36psi.

EFFECT OF WATER MASS FLOW RATE ON THE RATE OF HEAT TRANSFER

The study aimed to determine the impact of flow rate on the rate of heat transfer in the heat exchanger. Initially, the volume flow rate of water entering the heat exchanger was controlled. However, the focus shifted to studying the mass flow rate instead. The mass flow rate refers to the mass of fluid passing through a specific point. Specifically, the investigation concentrated on the quantity of working fluid passing through the cooling coil in the heat exchanger, to ascertain the rate of heat transfer at different flow rates. The volume flow rate varied at 2, 4, and 6 L/min, with measurements taken at regular intervals of 30 seconds up to 300 seconds. The results indicated a significant temperature drop when the power supply was set at 150W and the pressure at 36psi. Consequently, the overall data were collected under the conditions of 36psi and 150W. In Table 2, the impact of R-134a volume flow rate on the temperature drop between points T2 and T3 in the heat pipe area is presented, while Table 3 illustrates the influence of water volume flow rate on the temperature drop between points T5 and T6 in the heat exchanger.

Table 2. Effect of R-134a volume flow rate on temperature drop (Between points T2 – T3)

Time (s)	Volume Flow Rate (L/min)					
	2 L/min		4 L/min		6L/min	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
30	48.6	27.3	54.9	28.8	38.6	29.9
60	51.2	27.4	55.7	28.8	38.9	30.0
90	53.8	27.5	56.6	28.8	39.4	30.1
120	56.3	27.5	57.6	28.9	39.5	30.1
150	58.7	27.6	58.7	29.0	39.8	30.1
180	60.9	27.7	59.7	29.1	39.8	30.1
210	63.1	27.8	60.4	29.1	40.3	30.1
240	65.2	27.9	61.1	29.2	40.6	30.3
270	67.1	27.9	61.7	29.2	41.2	30.3
300	68.9	28.0	62.3	29.3	41.2	30.3
Average	59.4	27.7	58.9	29.0	39.9	30.1
Temperature Drop (°C)	31.70		29.85		9.80	

Table 3. Effect of water volume flow rate on temperature drop (Between points T5 – T6)

Time (s)	Volume Flow Rate (L/min)					
	2 L/min		4 L/min		6L/min	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
30	24.1	27.6	24.1	28.8	38.6	29.9
60	24.1	27.6	24.1	28.8	38.9	30.0
90	24.1	27.6	24.1	28.8	39.4	30.1
120	24.1	27.6	24.1	28.9	39.5	30.1
150	24.1	27.7	24.1	29.0	39.8	30.1
180	24.1	27.6	24.1	29.1	39.8	30.1
210	24.1	27.7	24.1	29.1	40.3	30.1
240	24.1	27.7	24.1	29.2	40.6	30.3
270	24.1	27.7	24.1	29.2	41.2	30.3
300	24.1	27.7	24.1	29.3	41.2	30.3
Average	24.1	27.7	24.1	29.0	39.9	30.1
Temperature Drop (°C)	3.55		3.74		4.71	

Both tables exhibit significant disparities in temperature drop for R-134a and water. At a volume flow rate of 2L/min, R-134a experienced a temperature drop of 31.70°C, whereas water exhibited a temperature drop of 3.55°C. However, as the volume flow rate increased to 6L/min, the temperature drops for R-134a decreased to 9.8°C, while water's temperature drop increased to 4.7°C. The summarized result of the heat transfer rate for both working fluids is presented in Table 4.

Table 4. Summarize the result of the heat transfer rate

Type	Mass Flow Rate (kg/s)	Temperature Drop, ΔT (°C)	Specific Heat, C_p (J/kg.K)	Heat Transfer, $\bar{Q}$ (J/s)
Water	0.03	3.55	4179.65	445.13
	0.07	3.74	4179.61	1038.79
	0.1	4.71	4179.42	1968.51
R-134a	0.014	31.72	1145.04	508.49
	0.030	29.85	1145.90	1026.15
	0.177	9.8	1128.06	1956.73

Table 4 reveals an interesting relationship between the mass flow rate and temperature drop for water and R-134a. It demonstrates that the mass flow rate for water is directly proportional to the temperature drop, while for R-134a, it is inversely proportional. However, in real-life systems, the temperature drops should ideally behave oppositely to the mass flow rate. Specifically, as the mass flow rate increases, the temperature difference should decrease. To explain this phenomenon, when the mass flow rate is high, it takes more time for water molecules to heat up. As a result, the temperature drop becomes less pronounced. This allows the heat exchanger to dissipate more heat into the water during the condensation process. It is important to note that in this project, no mechanical parts such as pumps or compressors were used to increase the mass flow rate in the closed system. The observed relationship between mass flow rate and temperature drop is a natural consequence of the system's characteristics.

Eq. (1) is used to obtain the rate of heat transfer,

$$\Delta Q = \dot{m} C_P \Delta T$$

(1)

where

ΔQ = Rate of heat transfer (J/s)

$\dot{m}$ = Mass flow rate (kg/s)

C_P = Specific heat (J/kg.K)

ΔT = Temperature difference (K)

From Eq. (1), the values ΔQ are obtained. The data demonstrates that as the mass flow rate of both water and R-134a increases, there is a corresponding increase in the amount of heat transfer. This establishes a direct relationship, indicating that the mass flow rate of the working fluids is directly proportional to the heat transfer rate.

EFFECT OF PRESSURE ON THE RATE OF HEAT TRANSFER

The pressure value applied to the flat heat pipe was controlled to investigate its impact on the heat transfer rate in a heat exchanger. It represents the quantity of working fluid present in the enclosed system, considering that the physical properties of gas occupy space. Based on several experimental data, it was observed that there is a significant temperature drop when the power supply is set to 150W, and the maximum heat transfer occurs at a volume flow rate of 6L/min. Consequently, the analysis focuses on the results obtained at 150W and 6L/min. To explore the relationship further, the volume flow rate was varied at 2L/min, 4L/min, and 6L/min, while measurements were taken every 30 seconds up to 300 seconds. Table 5 presents the recorded results for both water and R-134a at three predetermined pressures.

Table 5. The total result of heat transfers for water and r-134a

Working Fluids	Water			R-134a		
Pressure, psi	12	24	36	12	24	36
Temperature Drop, (°C)	4.49	4.49	4.70	2.28	6.60	9.80
Density (kg/m³)	996.73	996.73	996.71	37.48	39.34	43.45
Mass Flow Rate (kg/s)	0.099673	0.099673	0.099671	0.773444	0.264267	0.181911
Specific Heat, Cp (J/kg.K)	4179.46	4179.46	4179.42	1060.67	1072.40	1098.24
Heat Transfer (W)	1870.441	1870.441	1957.864	1870.44	1870.44	1957.865

Table 5 reveals that the rate of heat transfer reaches its maximum when the flat heat pipe is filled with 36psi, corresponding to 1957.86W of power. This observation implies that higher pressure levels facilitate more efficient heat transfer in the heat exchanger. By applying increased pressure, higher temperatures are attained, leading to a greater temperature differential. As a result, a significant enhancement in heat transfer is achieved. In summary, when operating at high power levels, increasing the pressure enhances the heat transfer process (Archana et.al, 2015).

HEAT EXCHANGER EFFICIENCY

In this study, we also aim to compare the efficiency of a heat exchanger with different designs to that of a flat heat pipe. The efficiency of the heat exchanger is determined by

analyzing the maximum heat transfer achieved, considering that the condensation process does not occur within the heat pipe itself. Our calculations are based on the optimal parameters obtained from previous experiments conducted on the flat heat pipe. These parameters are as follows:

Pressure = 36 psi
Volume Flow Rate = 6 L/min
Power = 150W

The efficiency of the heat exchanger can be obtained from Eq. (2) and Eq. (3).

$$\varepsilon = \frac{Q_{actual}}{Q_{\max imum}}$$

(2)

where;

Q_{actual} = maximum value of heat transfer = 1957.86W

$Q_{\max imum} = (\dot{m} \times C_p) \times (T_{h_{in}} - T_{c_{out}})$ = 3160.78W (3)

Hence, we have determined that the efficiency, ε of the crossflow heat exchanger (Design 1) employing R-134a is 0.62. In Table 6, we provide a comprehensive comparison of the efficiency between the crossflow heat exchanger using R-134a and water, along with another design option, namely the counter-flow heat exchanger. It is worth noting that the data from previous experiments, which involved highly comparable testing and data collection techniques, have not been included in this study.

Table 6. Comparison of Efficiency of Heat Exchanger

Type	Design 1	Design 2	Design 3
Heat Exchanger	Crossflow	Crossflow	Counter-flow
Working Fluid	R-134a	Water	R-134a
The efficiency of the Heat Exchanger, ε	0.62	0.52	0.45

The findings reveal that the efficiency of a crossflow heat exchanger utilizing R-134a as the working fluid surpasses that of the counter-flow type and water in similar configurations. This is primarily attributed to the heat exchanger's larger surface area compared to the alternative design. A larger conducting interface surface area results in a higher heat transfer rate. Furthermore, experimental evidence confirms that the crossflow heat exchanger type exhibits significantly greater efficiency compared to the counter-flow heat exchanger.

CONCLUSION

In this experimental study, a flat heat pipe was fabricated and tested with two different working fluids. The resistance heater used in the experiment was capable of supplying power up to 750W, while the maximum power capacity of the closed evaporator-condenser system design of the heat pipe was limited to 150W. The flat heat pipe was successfully filled with R-134a without any leakage, ensuring that the heat pipe could maintain the precise pressure required for the experiment. It is crucial to prevent leakage, as it would compromise the heat pipe's ability to function optimally.

The research findings revealed that the crossflow type, utilizing R-134a as the working fluid, outperformed the other two comparative configurations, with an efficiency of 0.62. The effectiveness of the heat exchanger directly indicates the efficiency of the flat heat pipe in transporting heat from a medium. Overall, this study successfully demonstrated the fabrication and testing of a flat heat pipe, highlighting the importance of selecting the

appropriate working fluid and heat exchanger configuration to achieve optimal heat transfer efficiency.

In future studies on heat pipes, several areas can be explored to further understand their behavior and optimize their performance. One such area is the investigation of container materials and their impact on heat transfer. By varying the container material, researchers can analyze how different materials influence the overall heat transfer characteristics of the heat pipe. Additionally, it is important to test heat pipes in various environmental conditions to assess their performance under different scenarios. This includes conducting experiments in cold places, high-altitude locations, and even underground environments. By subjecting heat pipes to these diverse conditions, researchers can gain insights into their adaptability and effectiveness in real-world applications.

Furthermore, exploring the effect of different orientation angles on heat pipe performance is essential. Heat pipes can be tested in both horizontal and vertical orientations to understand how gravitational forces affect their operation. This analysis can provide valuable information on the optimal orientation for heat pipes in specific applications and environments. By incorporating these factors into future studies, researchers can deepen their understanding of heat pipe behavior and develop more efficient and versatile designs. This knowledge will contribute to advancing heat transfer technologies and expanding their range of applications.

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