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Experimental Study on Thermal Performance of a Heat Pipe Using Different Refrigerants as a Working Fluid

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ABSTRACT

Heat pipes, meanwhile, refer to an efficient and passive cooling device utilizing the liquid phase change of the circulating fluid in transferring latent heat. An elementary design of a copper heat pipe was developed and constructed, taking refrigerant R-600a and R-134a as the working fluid. Experimental data were taken and analyzed from 46ºC over 90 minutes with measurements taken every 10 minutes. Consequently, the average cooling rates were found 0.100ºC min^{-1} for R-600a and 0.101ºC min^{-1} for R-134a. However, R-600a faster initial pull down in temperature till 40ºC whereas R-134a showed greater late stage approach to lower set-point temperature till 38ºC. Evidently, the results confirm that the selection of working fluid should be based on operating temperature regime for better outcomes as well as both refrigerants are efficient in thermal management which can be employed as an eco-friendly alternative to conventional refrigerants in heat pipe applications.

Keywords: Heat Pipe, R-600a, R-134a, Thermal Efficiency, Phase Change

1. Introduction

The ability to regulate as well as enhance heat transfer methods is crucial to the improvement of reliability, performance, and environmental consciousness across a variety of applications, such as but not limited to electronics cooling, and generation of electricity, Hence, there is an increasing focus on establishing passive, economical solutions to enhance thermal performance while minimizing significant rises in hydraulic resistance [1]. The solutions that have been investigated among various passive cooling solutions, heat pipes (HPs) have been identified for their high effective thermal conductivity, simple structures, and high capacity despite small temperature gradients. On one side, the basic structure of the conventional heat pipe consists of an evaporator, an adiabatic section, and a condenser, in which the liquid undergoes continuous evaporation and condensation, effectively transferring its latent heat. However, the efficiency of the heat pipe strongly depends on the wicking material and fluid, both of which play significant roles in defining capillary action at the operating temperature. Moreover, growing public awareness of the ozone-depleting problem and the presence of high global warming potential (GWP) refrigerants in modern air conditioners has triggered global efforts to find more eco-friendly alternatives. Hydrocarbons such as R-600a (Isobutane) and emerging hydrofluoroolefins (HFOs) such as R-1234ze and R-1233zd (E) offer significant benefits, including low environmental impact, desirable properties, and efficiency. Korkmaz and Ermiş [2] conducted an experimental study to evaluate R-1234ze for cooling CPUs in laptops using heat pipes, comparing it with the water–methanol combination, which served as the reference fluid. They concluded that R-1234ze could achieve lower CPU temperatures in idle mode, indicating its potential as a replacement for the former. Hannah and Anand [3] tested the thermosyphon heat pipe using R-134a and R-600a refrigerants. It has been observed that R-600a provided an evaporator heat transfer coefficient roughly 16% higher and a lower thermal resistance. Their machine learning models (SVM, ANN, and CNN) achieved over 95% prediction accuracy, confirming strong agreement with experimental data. Sistaninia et al. [4] examined the utilization of heat pipes as inlet air-cooling systems for gas turbines to raise power output. Their optimised design achieved a maximum heat transfer rate of 1.4878 kW per HP at 40°C, increasing turbine output by up to 18.6%, confirming the potential of HP-based heat exchangers for power enhancement. Yilmaz and Cimsit [5] experimentally integrated a thermosyphon-type loop heat pipe into the circuit of a 20kW vapor compression refrigeration cycle. A higher COP was achieved in the system, from 3.12 to 3.19, with reduced compressor power and CO_2 emissions, proving the energy-saving and environmental benefits of integrating HPs. Wu et al. [6] investigated a pulsating heat pipe with R-1233zd(E) and obtained the lowest thermal resistance of 0.1184 °C/W at an optimum filling ratio of 50-60% with 1.5 mm inner diameter. They also proposed an empirical correlation with 95% prediction accuracy, confirming R-1233zd(E) as an efficient low-GWP working fluid. Islam et al. [7] designed and tested a heat pipe using R-134a, resulting in approximately 47% reduction in cooling time under natural convection and up to 68% under forced convection. A comprehensive review by Fagri [8] summarized several types of heat pipes, principles of operation, and compatibility of materials with fluids; he noted that a typical heat pipe would include a sealed container, wick structure, and working fluid in vapor–liquid equilibrium. Velkumaran et al. [9] developed and constructed a refrigerator using R-600a, highlighting its low ozone depletion potential (ODP), non-toxicity, and cost-effectiveness. Rasti et al. [10] investigated a household

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refrigerator with R-436A (a blend of R-290 and R-600a). They reported that it reduced energy consumption by 5.3% and total equivalent warming impact (TEWI) by 11.8% relative to R-134a, confirming the blend's superior environmental and energy performance. Zahidul et al. [11] tested a vertical heat pipe using R-22 under free and forced convection and reported that the cooling time was reduced by up to 70% under forced convection compared with free convection. Yau et al. [12] reported that heat pipes were superior to solid metallic conductors such as copper and silver because they could transfer latent heat over long distances with minimal temperature differences. Experimental and numerical studies [13] have elucidated the mechanisms of heat transfer in the liquid-wick and wall regions, using mostly one-dimensional heat-conduction models. The proper selection of a wick structure and working fluid becomes crucial for appropriate heat pipe performance. [14]. For example, wire-mesh wick structures have exhibited consistent capillary behaviour with refrigerants like R-22 [15]. R-22, an HCFC, was widely adopted due to its moderate pressure and favorable heat transfer properties. However, its high ODP has led to regulatory phase-outs [16]. Recent research has focused on advanced working fluids, such as nanofluids. Iron oxide nanoparticles added to water provided enhanced heat transfer performance and reduced thermal resistance of thermosyphon heat pipes [17]. Flexible looped heat pipes (FLHPs) charged with R-134a have been shown to transport high heat over long distances effectively and to operate stably under various orientations [18].

Most studies have used R-22, R-134a, or other conventional refrigerants in heat pipes, while limited experimental research has been conducted on R-600a under natural cooling. In this paper, a simple copper heat pipe with wire-mesh wick is designed and fabricated using R-600a as the working fluid. The thermal performance is experimentally investigated and compared with natural cooling and an R-134a-based heat pipe to establish R-600a as an efficient, sustainable, and environmentally friendly refrigerant for future heat pipe-based thermal management systems.

2. Materials and Methodology

2.1 Structural Parameters of Heat Pipe

The heat pipe can be any size or shape and is mainly used to convey heat. A sealed container, a wick structure, and a small amount of working fluid in equilibrium with its own vapor comprise a heat pipe. Depending on the needed operating temperature, several working fluids can be utilized in heat pipes. The evaporator, adiabatic, and condenser sections are distinct.

The latent heat of vaporization can also be constantly transferred from the evaporator to the condenser section via the heat pipe**.**

2.2 Mechanism of The System

The experimental procedure was initiated by introducing the working fluid into the heat pipe, ensuring proper filling and sealing. The setup was then prepared by heating water in a container to 46 °C using an electric heater. Once the desired temperature was reached, the water was allowed to cool naturally, and its temperature was measured at 10-minute intervals with a mercury thermometer to establish a baseline cooling curve. In the next stage, the water was reheated to 46 °C, and the heat pipe was immersed in the container. The temperature of both the hot water and the condenser section of the heat pipe was measured at regular intervals during the cooling process. This approach enabled a direct comparison between the natural cooling of water and its performance when assisted by the heat pipe, providing valuable insights into its heat transfer characteristics and effectiveness.

Table 1 Structural Parameters of Heat Pipe

Parameter	Value
Diameter of pipe	25.4 mm
Wall Thickness	1 mm
Length of condenser	170 mm
Length of evaporator	140mm
Length of Adiabatic Section	140mm
Fin Dimension	(150mm×70 mm)
Number of Fin	5
Working fluid	R600a
Fill ratio	58%
Wick Type	Wire mesh
Insulator for adiabatic section	Glass wool

The working fluid is introduced into the heat pipe, as shown in Fig.1

Fig.1 Working fluid enters the heat pipe

2.3 Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 2. It consists of a heater, a mug filled with hot water into which the heat pipe's evaporator section was immersed, and a mercury thermometer. A copper tube was used to build the heat pipe. The tube measured 450mm in length and 25.4mm in diameter. The wick structure was made out of wire mesh. The evaporator, adiabatic, and condenser sections all have lengths of 170mm, 140mm, and 140mm, respectively. Glass wool and tape were used as insulation in the adiabatic portion. A rectangular tin fin measuring 150×70 mm was incorporated into the condenser section. The evaporator's temperature was thought to be the same as the water's temperature. The condenser temperature was measured with a K-type thermocouple, and the hot water temperature was measured with a mercury thermometer, which corresponded to the evaporator temperature.

2.3.1 Experimental Setup of Natural Cooling Without a Heat Pipe

The experimental setup is shown in Fig. 3. It consists of a heater, a mug filled with hot water into which the heat pipe's evaporator section was immersed, and a mercury thermometer. No heat pipe was used in this section.

Fig.2 Experimental setup of natural cooling without a heat pipe

2.3.2 Experimental Setup of Natural Cooling with Heat Pipe

The experimental setup is shown in Fig. 3. It consists of a heater, a mug filled with hot water into which the heat pipe's evaporator section was immersed, and a mercury thermometer. A heat pipe was used in this section.

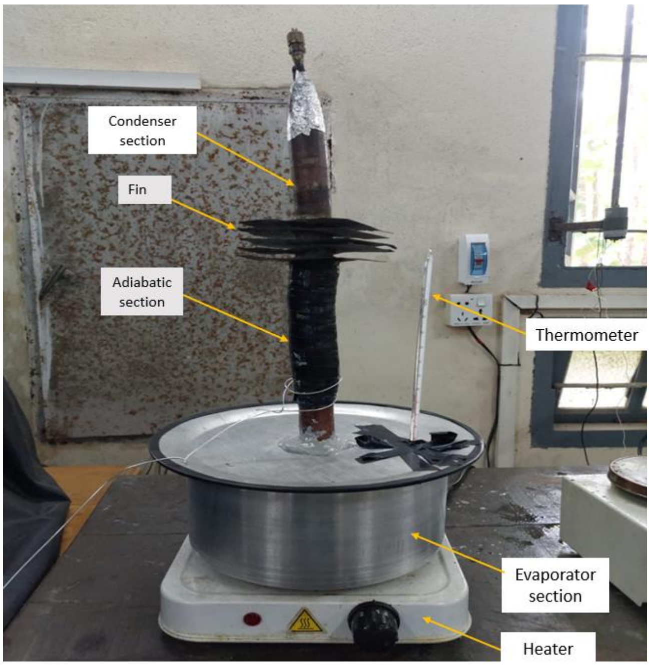

Fig.3 Schematic diagram of the experiment.

2.4 Working Principle of R-600a Refrigeration System

R-600a is stored in the high-pressure cylinder. A regulator is connected to a gas cylinder, and when it is opened, R-600A passes through the high-pressure pipe. This high-pressure R-600A then entered a capillary tube already connected to the high-pressure pipe. As the capillary tube has a small diameter, the pressure of R-600A drops, and the temperature also reduces. As a result, a phase change from liquid to vapor occurs. At that time, evaporation takes place. The low-pressure and low-temperature vapor absorbs heat from the evaporator section.

2.5 Data Collection: Cooling Time for R600a

The experiment lasted 90 minutes, with temperature measurements taken every 10 minutes. At the very start (0 minutes), both systems (with and without a heat pipe) recorded a temperature of exactly 46°C. As time progressed, the system without the heat pipe showed a gradual decrease in temperature. For example, after 10 minutes the temperature dropped to 44.2°C, and by the end of the experiment (90 minutes) it had reached 38°C. In contrast, the system with the heat pipe consistently maintained lower temperatures at all-time intervals. At 10 minutes, the recorded temperature was 43.2°C, compared to 44.2°C without the heat pipe. This trend continued throughout the test, and at every checkpoint, the heat pipe setup showed improved cooling efficiency. Overall, the descriptive data clearly demonstrate that the heat pipe enhanced heat dissipation, resulting in lower system temperatures during the entire 90-minute test. These results validate the thermal performance advantage of the heat pipe over natural cooling.

2.6 Data Collection: Cooling Time for R134a

The updated experimental data were recorded over 90 minutes, with temperature readings taken every 10 minutes. At the beginning, there was no temperature difference, as both systems (with and without the heat pipe) measured 46°C. As time progressed, the temperature of both systems gradually decreased, but the system with the heat pipe consistently showed a slightly greater decline. For example, at 10 minutes, the temperature without the heat pipe was 44.7°C, while with the heat pipe it was 44°C. This consistent pattern continued throughout the test. By the end of the experiment (90 minutes), the temperature without the heat pipe had dropped to 36.9°C, whereas with the heat pipe, it was 36.3°C, indicating a marginally lower temperature. These observations clearly indicate that using a heat pipe provided a measurable improvement in heat transfer and cooling performance. At every interval, the temperature with the heat pipe remained lower than without it, demonstrating its enhanced thermal management. It should be noted, however, that these findings are specific to the experimental setup used, and further testing under varied operating conditions would be required to generalize the results.

3. Result and Discussions

The experiment's outcome, therefore, confirms that a heat pipe provides a noticeable improvement in cooling efficiency compared to natural cooling. This was indicated in Fig. 4, which showed that applying the heat pipe resulted in a significant reduction in temperatures in the evaporator section compared to the case without a heat pipe. Specifically, in the first 10 minutes, the reading was 43.2°C, compared with 44.2°C recorded when using natural cooling. This will persist for 90 minutes due to the heat pipe's higher efficiency in absorption, conductivity, and diffusion. These levels, therefore, shall be indicated in the two-phase process transferring heat from or to the liquid with lower temperatures. Specifically, when showing efficiency in applying heat in the evaporator section, since it contains a liquid, namely R-600a, the fluid shall vaporize at higher temperatures, then move to the condenser section, releasing

Latent heat in the process, subsequently transforming back to liquid. Similar results were obtained across different studies, where heat pipes exhibited faster cooling and higher heat transfer rates than natural convection. For example, in studies on heat pipes with nanofluids, enhanced thermal conductivity and performance were achieved through improvements in absorption and phase-change efficiency [19]. Another study emphasized that heat pipes have a higher capacity for heat transfer in energy systems, whereby the two-phase mechanism and the release of latent heat enable rapid temperature reduction and improved thermal management under varying operating conditions [20]. Experimental studies conducted on heat pipes have also established that their ability to sustain efficient vapor-liquid cycling enables rapid cooling and greater heat dissipation compared to conventional convection methods [21]. These agree with the results of this experiment and further show that heat pipes exhibit higher cooling capacities.

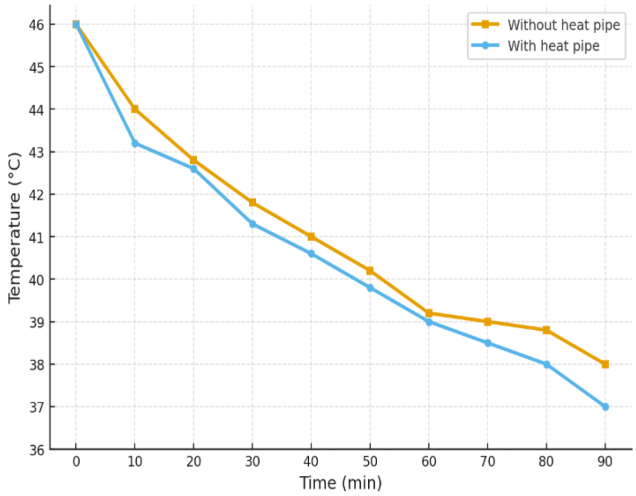

Fig.4 Temperature of hot water with and without the application of the heat pipe over time

Fig. 5 Cooling Curve Comparison Between Two Working Fluids, R-600a, & R-134a under the same experimental set-up. According to Fig. 5, both R-600a and R-134a, with an initial temperature of 46ºC, had a constant cooling rate per unit time. However, despite the cooling pattern, R-134a, which had cooled to 36.9ºC, was lower than R-600a, which had cooled to 37ºC. This was attributed to their properties. Since R-134a has a lower boiling point of -26.3ºC, it vaporizes more readily, resulting in a higher cooling rate [22]. However, in the case of R-600a, its high latent heat of vaporization and thermal conductivity provided efficient cooling with minimal energy loss. Moreover, R-600a had lower pressures, hence safer and more environmentally friendly. Since R-134a, with its higher cooling rate, was replaced by R-600a, which offers more efficient cooling, R-600a has proven to be environmentally friendly due to reduced energy consumption. Similar findings were reported in an experimental study on heat pipes using refrigerant R-22, which showed significantly faster cooling and higher heat transfer rates than natural convection. The study confirmed that heat pipes' two-phase mechanism and latent heat absorption result in rapid temperature reductions and superior thermal management, supporting the results of this

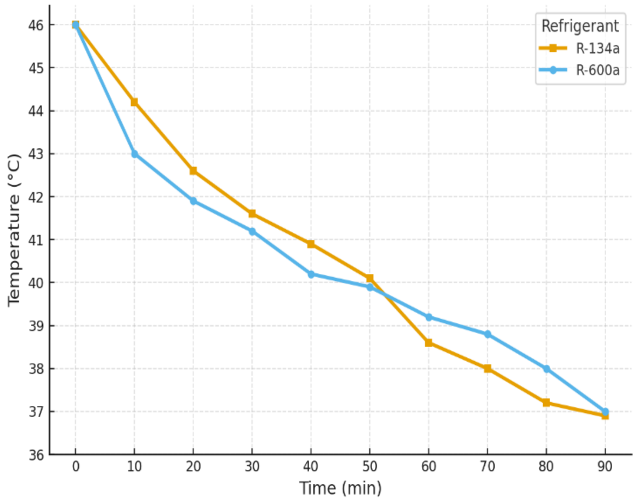

Fig.5 Temperature of hot water with the application of the heat pipe over time for the different working fluids

experiment [11]. Overall, the observed temperature variation between the two systems is attributed to the distinct phase-change characteristics and cooling capacities of the respective refrigerants. From the experimental outcomes, one can note with certainty that the usage of the heat pipe enhances cooling speeds and the speed of the phase change process in both R-600a and R-134a, with minimal variation between the two, both of which can be regarded as suitable work fluids, with R-600a being more environmentally friendly, stable, and efficient.

4. Conclusion

Designing and fabricating a heat pipe with refrigerants R-600a and R-134a as the working fluids is a crucial operation that requires careful consideration of several variables. A well-made heat pipe can deliver reliable, efficient heat transfer across a range of applications. A properly constructed and engineered heat pipe can provide effective, dependable heat transfer across a variety of applications. According to the experimental findings, cooling a hot body from 46°C to 40°C using the refrigerant R-600a as the working fluid occurs, on average, 1.32% faster than with R-134a. On the contrary, while a late stage approach to 38ºC, it was observed that R-134a was 12.5% faster than R-600a. In comparing two refrigerants, the cooling rate slows over time as the temperature difference decreases. For many heat transmission applications, the heat pipe is the preferred device. Refrigerant can improve heat pipe performance and be used over a wide range of temperatures by adjusting its operating pressure. To facilitate the present findings, nano-refrigerants can be incorporated into R-134a and R-600a by dispersing Al_2O_3, CuO, TiO_2, or graphene using compatible dispersants, thereby improving the thermal conductivity and heat transfer performance of the working fluid.

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