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Influence of Evaporator Length and Inclination on the Performance of Acetone-Filled Heat Pipe

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Abstract: **-** Heat pipes serve as efficient tools for transferring heat between different points in closed-loop systems. The behaviour of heat pipes depends on various factors such as geometry, physical properties, and operational conditions. Therefore, parameters like evaporator length, input power to the evaporator, and tilt angles are analyzed during the investigation process. The heat pipe was designed to contain acetone filling up 50% of the evaporator volume. Testing was conducted with heat inputs ranging from 40W to 120W, at orientations of 45° and 90°. The heat pipe's performance is evaluated based on key parameters such as effectiveness, thermal resistance, and temperature gradient under varying heat inputs and inclinations. Effectiveness improves as heat input rises from 40W to 120W, with greater efficiency seen in a 125 mm evaporator length and a 90° inclination. Thermal resistance is minimized with a 125 mm evaporator and 100 W input. Lower heat inputs correspond to reduced temperature gradients, indicating faster heat transfer rates. Notably, the heat pipe demonstrates exceptional performance in terms of effectiveness and thermal resistance at a 90° tilt and 125 mm evaporator length.

Keywords*: Evaporator Length, Inclination, Acetone Filled, Heat Pipe. Heat Pipe behavior.*

1. Introduction

Heat pipes are innovative heat-transfer devices that effectively handle heat transfer by combining thermal conductivity and phase transition principles. The idea of heat pipes was initially proposed by Gaugler in 1942. By utilizing the latent heat of the vaporized working fluid and a minimal temperature gradient through the phase change of the working fluid, heat pipes achieve significantly higher thermal conductivity compared to solid conductors. These devices offer numerous advantages in various applications such as heat recovery systems, solar energy, light water nuclear reactors, electronics cooling, and aircraft cooling.

A standard heat pipe is comprised of a sealed vessel, a wick system, and a minimal quantity of working fluid necessary to saturate the wick, and it is in balance with its vapour. The pressure at which the heat pipe operates is equivalent to the vapour pressure of its working fluid. The heat pipe's length is segmented into three parts: the evaporator, adiabatic, and condenser sections, as illustrated in Figure 1.

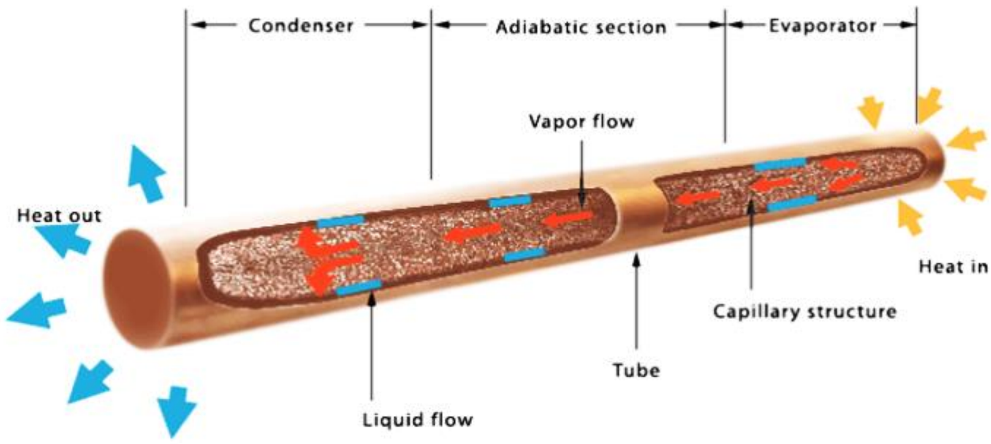

Figure 1: Heat pipe sections.

1.1 Working principles of heat pipe

A traditional heat pipe is a hollow cylinder filled with a vaporizable liquid.

- Heat is absorbed in the evaporating section.
- Fluid boils to the vapour phase.
- Heat is released from the upper part of the cylinder to the environment; vapour condenses to a liquid phase.
- Liquid returns by gravity to the lower part of the cylinder (evaporating section).

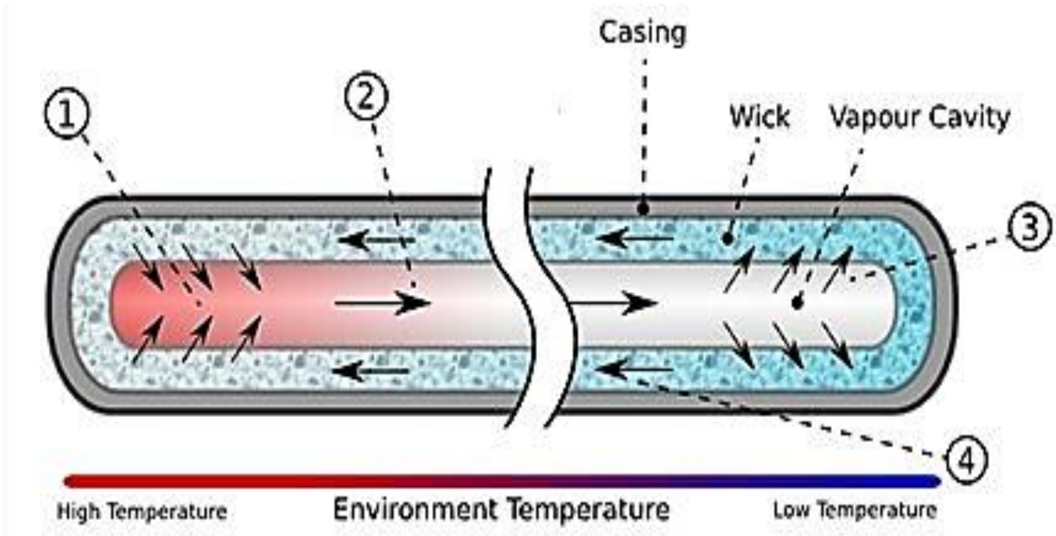

Figure. 1 Working principle: Heat Pipe.

Figure 2 illustrates the typical operational schematic of a heat pipe. In this setup, heat input into the evaporator section leads to the conversion of the working fluid into vapour, which then moves to the condenser region. Afterwards, the vapour condenses, giving off latent heat. The condensed liquid is then conveyed back to the evaporator portion via capillary action. Anjankar et al. [1] conducted a comprehensive analysis of the heat pipe's behaviour, investigating different flow rates in the condenser, varying heat inputs in the evaporator section, and diverse condenser lengths. The study findings indicated that the optimal performance was achieved at a flow rate of 0.0027 Kg/s, a heat input of 500 W, and a condenser length of 450 mm.

1.2 Geometrical and operational parameters.

Geometrical parameters: The efficiency of the heat pipe is influenced by various factors, such as the aspect ratio (AR), section ratio (SR), different sections of the heat pipe (evaporator, adiabatic, and condenser), as well as the diameter and thickness of the container. The capillary action determines the return of condensate to the evaporator section and is dependent on the length of the heat pipe. Additionally, a decrease in diameter can result in higher losses and subsequently, reduced performance when considering a particular heat input. El-Genk et al. [2] have identified the key factors that affect the performance of a heat pipe, including its diameter, evaporator length, and working fluid temperatures. It is worth noting that among these factors, the evaporator length has a more pronounced impact. Rittidech and his team (2019) conducted a study specifically on the effect of evaporator length on heat transfer efficiency and concluded that a shorter evaporator length enhances heat transfer. In a separate investigation, Yamamoto (2020) found that a larger diameter leads to higher heat flux. Furthermore, Peterson (2021) emphasized the significant influence of the length of liquid transport on heat performance. Furthermore, it was discovered by Hudakorn and colleagues in 2022 that heat pipes of greater diameters demonstrate increased heat flux. In a separate study, Shivaraman and team in 2023 investigated the impact of different geometrical factors, including diameter and length, on the rates of heat transfer.

Effect of operational parameters: The thermosyphon tube is influenced by various factors such as power input, tilt angles, and flow patterns. In their studies, Imura et al. [8] and Groll et al. [9] found that increasing the tilt angle and operating temperature resulted in enhanced heat transfer capability. On the other hand, Gurses et al. [10] and Bilegan et al. [11] observed no significant impact of gravity on heat pipe performance when in a horizontal position. However, as the inclination changes, the role of gravity becomes evident. Shirashi and colleagues (2012) as well as Hasan and team (2013) demonstrated superior performance in the vertical orientation, showing an increase in thermal resistance with higher inclination angles. On the other hand, Meyer et al. (2014) and Chowdhury et al. (2015) studied heat pipes in both vertical and inclined (45º) positions with a 50% fill ratio. Their findings indicated that vertical testing exhibited a greater temperature gradient and performed better. Literature suggests that the geometric and operational aspects of heat pipes significantly influence heat transfer characteristics. Therefore, the current study aims to explore the impact of heat input, evaporator section length, and tilt angle.

2. Problem Description and Experimentation.

The study focused on heat pipes with varying evaporator lengths, heat inputs to the evaporator, and inclinations, as these factors are essential in assessing the efficiency of the heat pipe. The efficiency of a heat pipe is affected by its geometric, physical, and operational properties.

- The evaporator lengths were 75,100 and 125 mm to be tried out.
- The design of the copper tube heat pipe involves a 25 mm diameter, 430 mm length, and 3 mm thickness.
- Acetone employed as working fluid with a 50% filling ratio.
- The heat input 40W to 120W.
- The temperatures were measured using copper-constantan K-type thermocouples arranged at 7 positions equally spaced along a line on the periphery of the heat pipe.

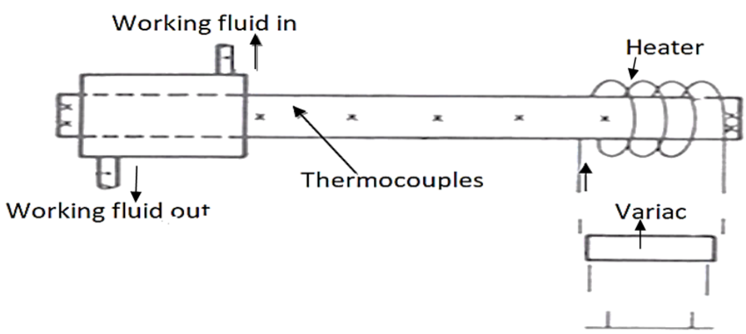

Figure 2: Schematic of experimentation of heat pipe.

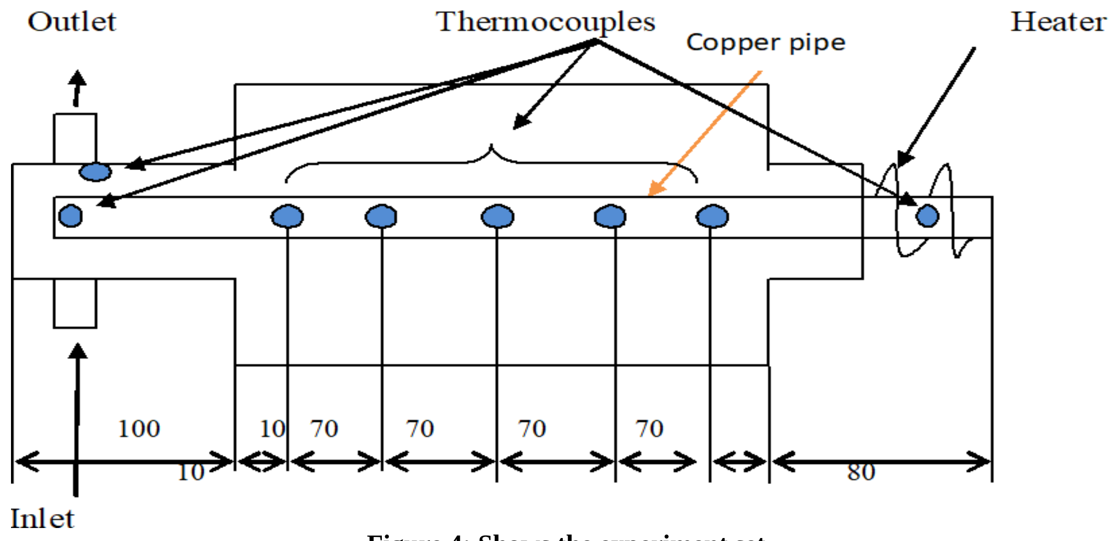

Figure 4: Shows the experiment set.

Figure 3 depicts the schematic of the heat pipe experimentation, while Figure 4 showcases the heat pipe geometry along with the thermocouple connections and locations. This specific heat pipe is made of copper and has a diameter of 25 mm, a thickness of 1.2 mm, and a length of 430 mm. It consists of an evaporating section measuring 80 mm and an adiabatic section measuring 300 mm. The evaporating section is filled with the working fluid, occupying 80% of its volume. To monitor the temperature, thermocouples of type K are utilized at 8 different points. These points include the inlet and outlet water of both the evaporating and condensing sections, as well as 5 different points on the outer walls of the heat pipe. The heat source consists of a stainless vessel with dimensions of Φ45X65 mm, which incorporates a heater. Heat is supplied to the evaporator section through a band heater powered by a 230V AC supply using a variator.

2.1 The heat pipe construction.

The heat pipe construction is as follows.

- A copper tube of suitable length is cleaned thoroughly with suitable cleaning agents.
- It is then closed by end caps at both ends.
- Thermocouples are equally spaced at various positions.
- A heating coil is wound over the mica sheet in a uniformly spaced manner.
- The two ends of the heating coil are connected to the power input.
- A few centimetres thick covers of glass wool are provided over the entire region of the thermosyphon.
- The heat pipe is evacuated to a pressure of -1.36atm for about 2 hours using a vacuum pump.
- The coolant water supply is provided to the heat pipe and can be controlled by a valve.
- A voltmeter is connected in parallel to the dimmer stat.
- The temperature scanner is connected to an electric power inlet through a voltage stabilizer.

Figures 5 (a) to 5 (i) display the detailed sections of the heat pipe, installation, and the instrumentations of the experimental setup. For the current study, three evaporator lengths of 125mm, 100mm, and 75mm were chosen, as depicted in Figure 5 (g). Figure 5 (f) illustrates the utilization of two pressure gauges to record vacuum pressure during idle conditions and gauge pressure during operation. Additionally, Figure 5 (b) to 5 (d) showcase the thermocouples and their connections at the condenser section, adiabatic section, and evaporator sections.

Figure 6 and Figure 7 show the completer heat pipe assembly instrumented and arranged in vertical position and 45° inclinations.

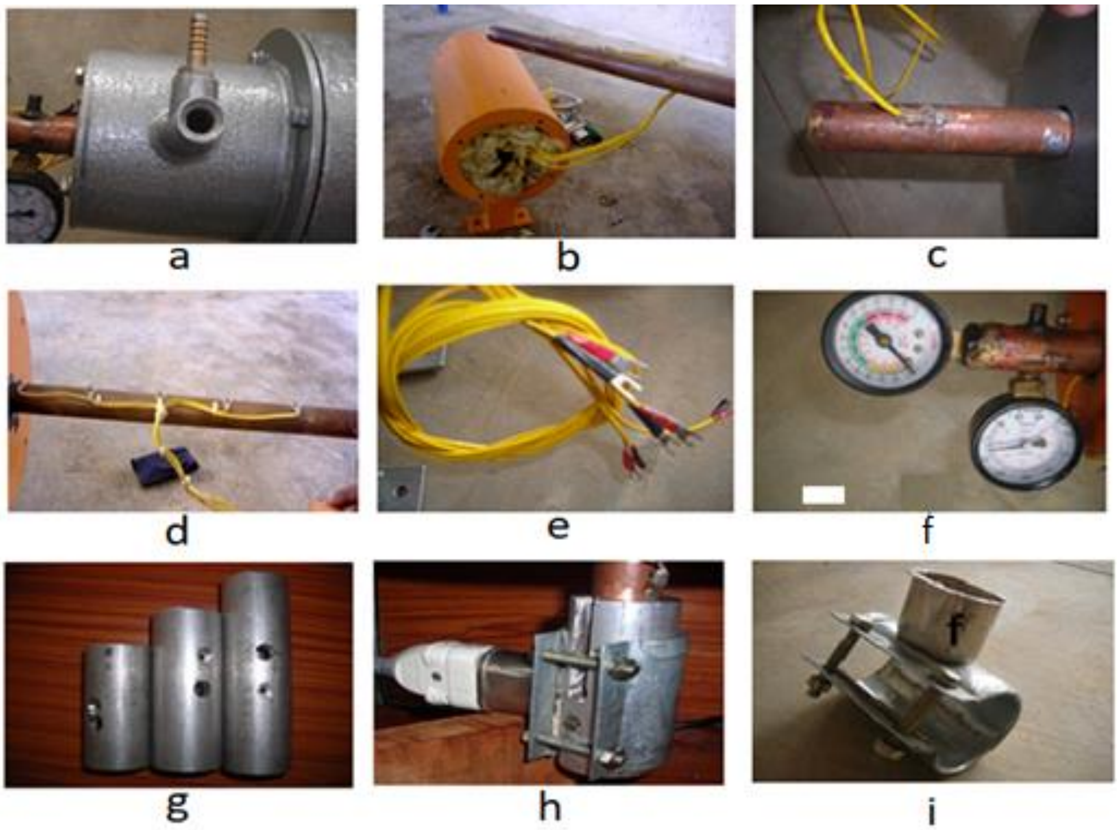

Figure 5: Components of heat pipe assembly a) Condenser section b) Adiabatic section c) Evaporator section d) Thermocouples on adiabatic section e) Thermocouple wires f) Pressure gauges g) Evaporator heating sections d) band Heater on evaporator section i) Band heater.

2.2 Heat Pipe Test Rig 90° and 45°.

6: Heat pipe test rig (90° tilt).

Figure 7: Heat pipe test rig (45° tilt).

3. Results and Discussions.

The study utilized acetone as the heat pipe fluid, with a fill ratio of 50%. The main focus was to investigate the impact of increased heat input (ranging from 40W to 120W) and pipe orientation (45° and 90°) on the heat pipe's performance. The performance was assessed based on thermal resistance, effectiveness, and temperature gradient. The experimental data was recorded and organized in a table, considering different evaporator lengths and inclinations as specified in the matrix. Throughout the experiments, a constant flow of condenser fluid was maintained. The evaluation of crucial parameters commonly used to assess heat pipe performance, such as heat pipe effectiveness, thermal resistance, and temperature gradient, was conducted. These evaluations were then presented graphically and thoroughly discussed in the subsequent sections.

3.1 Effectiveness with θ=90° (vertical orientation) and θ=45°.

The effectiveness of the performance can be seen in Figure 8 and Figure 9, where it is evident that the heat pipe inclined at a 90° angle to the horizontal outperforms the one inclined at a 45° angle. The trend of improved effectiveness with increased power input stays constant in all three scenarios, which include different evaporator lengths and orientation angles. The optimal performance is attained when the inclination is set at 90 degrees and the power output is 120W. This can be attributed to the swift reentry of acetone into the evaporator via the internal tube surface, following its condensation at the condenser.

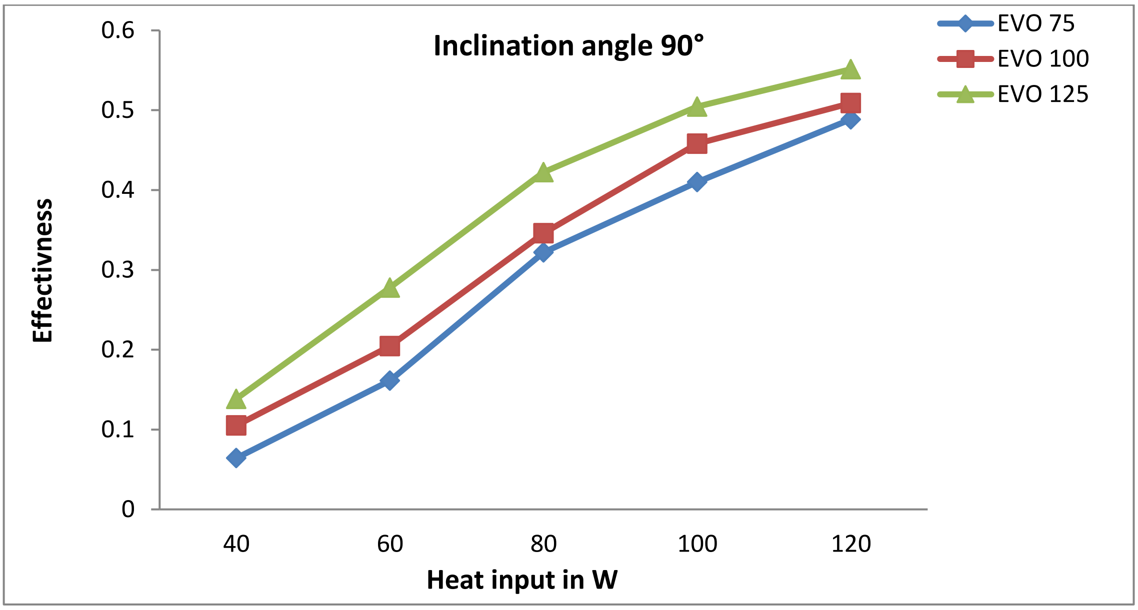

Figure 8: Effectiveness with varied heat input (90° orientation).

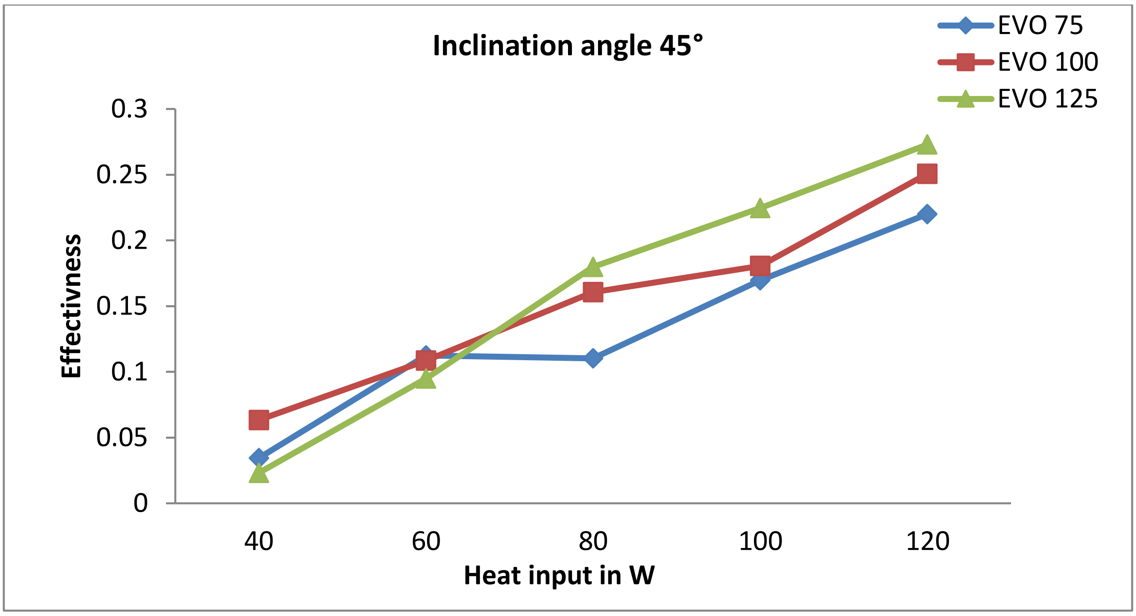

Figure 9: Effectiveness with varied heat input (45° orientation).

3.2 Thermal resistance (TR) with θ=90° (vertical orientation) and θ=45°.

Figures 11 and 12 illustrate the inverse correlation between thermal resistance (TR) and the gradual increase in power from 40W to 120W. The consistency of this pattern is maintained for tilt angles of both θ=90° and θ=45°. Moreover, it is important to emphasize that a higher heat input leads to a lower TR at a 90° tilt. On the other hand, the vertical orientation displays a more limited range of TR in comparison to a 45° tilt. This difference can be attributed to the decreased impact of gravity at a 45° inclination, as opposed to a 90° inclination. As a result, a higher TR is attained at a 90° tilt, which aligns with the observations made in the 100mm and 125mm evaporator sections.

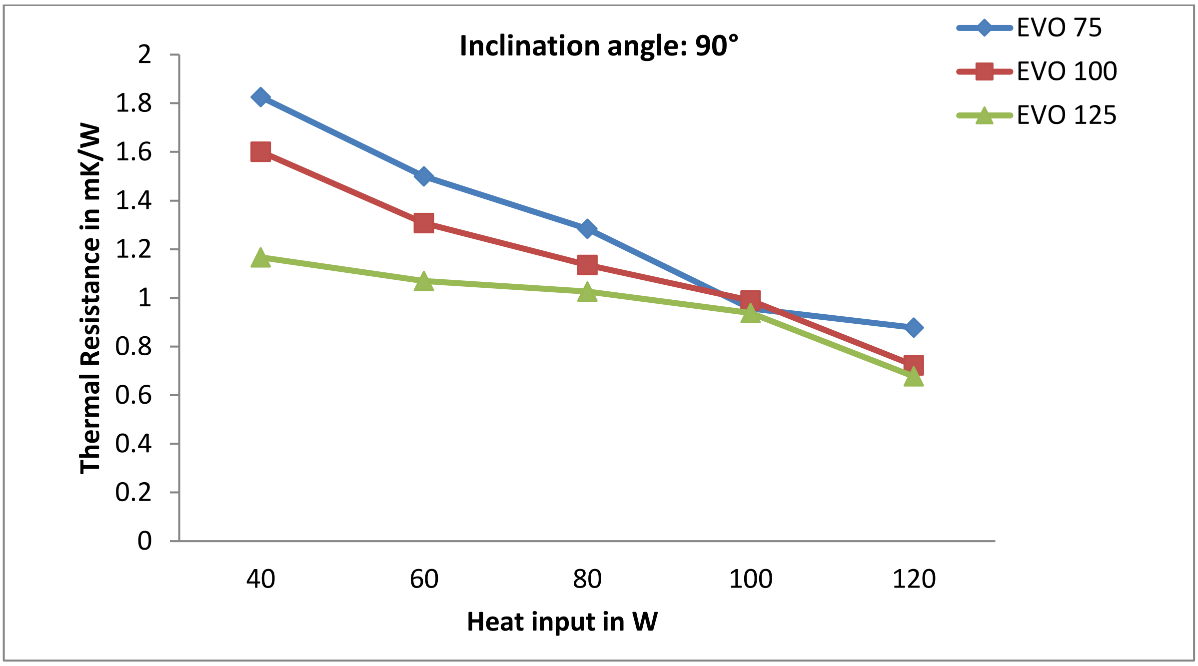

Figure 10: Thermal Resistance with varied heat input (90° orientation).

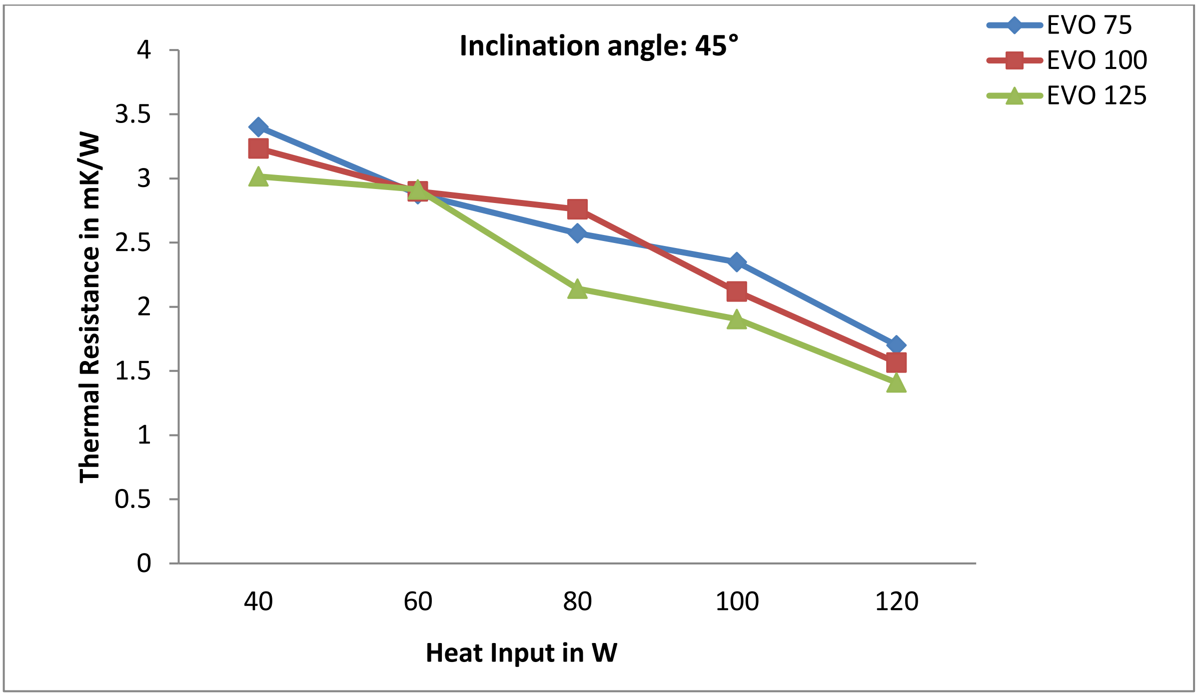

Figure 11: Thermal Resistance with varied heat input (45° orientation).

3.3 Temperature gradient with θ=90° (vertical orientation) and θ=45°.

The temperature gradient can be observed in Figure 12 and Figure 13, illustrating heat inputs ranging from 40W to 120W at angles of 90° and 45°. As the heat input increases, the temperature gradient consistently increases across the entire evaporator length. The relationship between the temperature gradient and power input remains consistent. However, a higher gradient is noticed when the inclination is 90° and the heat input is 120W. This phenomenon can be attributed to the influence of gravity on the movement of acetone in the heat pipe, leading to enhanced boiling and condensation processes. Consequently, the most efficient thermal performance is achieved when the tilt is at 90° and the power supply is at its maximum.

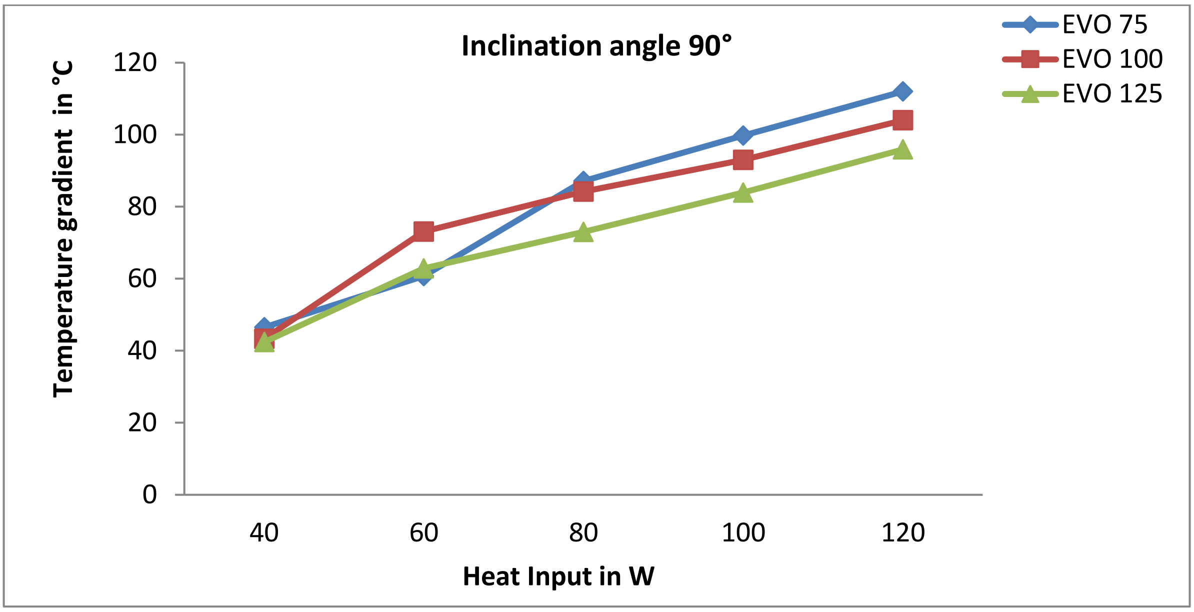

Figure 12: Temperature gradient with varied heat input (90° orientation).

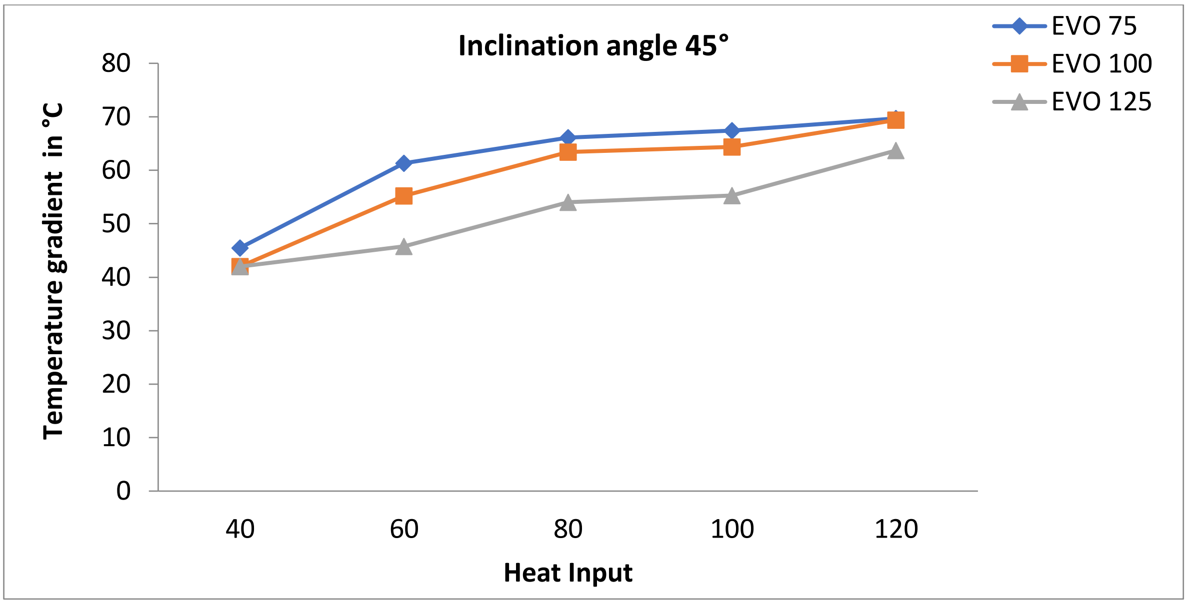

Figure 13: Temperature gradient with varied heat input (45° orientation).

4. Conclusions.

The present study focuses on analyzing the variations in temperature profiles resulting from diverse power supplies, evaporator lengths, and inclinations (45° and 90°). The results provide important insights into how different factors affect the efficiency, thermal resistance, and temperature variance of heat pipes. As a result, the conclusions drawn from the research are significant.

- The system's efficiency significantly improves with an increase in heat input from 40W to 120W. Moreover, optimal efficiency is achieved with a 125 mm evaporator length and a 90° tilt angle.
- The 125 mm evaporator provides a low thermal resistance for a 100 W input.
- A decrease in heat input will cause a reduced temperature gradient, resulting in a faster heat transfer rate, whereas a 90° incline will further enhance the speed of heat transfer.
- Finally, the conclusion can be made that the 125 mm evaporator length with 90° inclination provides good results as concerned with effectiveness.

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