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Investigating Temperature Effects on Thermal Analysis of Composite Heat Pipes with Diverse Geometrical Configurations

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Abstract

As the demand for efficient heat dissipation technologies continues to surge, understanding the intricate interplay between temperature variations and the thermal performance of heat pipes assumes paramount importance. This study investigates the impact of temperature fluctuations on the thermal behaviour of heat pipes with diverse geometric configurations. A comprehensive analysis is conducted utilizing advanced computational simulations coupled with experimental validation techniques. Heat pipes are an innovative heat transfer device with high thermal conductance and low thermal impedance that can transmit a considerable quantity of heat across a tiny cross sectional area while maintaining negligible temperature changes. In this paper, the thermal analysis was performed on the heat pipe with different geometrical configurations such as straight, L–bend, U–bend, wave, spiral form pipe. The analysis was performed using the FE software ANSYS 16.2 workbench to check the total heat flux generated in the heat pipe at an extreme temperature of 200°C and film coefficient of 10 W/mm^{2} ^{0}C Our investigation unravels the intricate influence of varying temperatures on heat transfer characteristics, fluid dynamics, and overall operational efficacy within heat pipes. Through the incorporation of novel design strategies and numerical models, we offer nuanced insights into the complex heat transfer mechanisms inherent in the heat pipe structure, particularly under diverse thermal conditions. Furthermore, this study delineates the pivotal role played by geometrical configuration in governing temperature distribution and thermal management within the heat pipe system. In this study, we expand the analysis by considering glass composite materials as the primary material for the heat pipes, deviating from the conventional use of copper in heat exchangers. The thermal analysis evaluates different geometrical configurations, comparing results across each pipe type to determine optimal values. This approach not only enhances the relevance of the study to the field of polymer and glass composite applications but also provides valuable insights into the thermal characteristics of glass composite-based heat pipes. The findings contribute to a deeper understanding of the interplay between temperature, geometry, and material composition in the context of efficient heat transfer technologies.

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Keywords: Temperature, Thermal analysis, Heat pipe, Geometrical configurations, Heat transfer, Computational simulations

INTRODUCTION

The heat pipe is a thermal device that uses fluid to convey heat efficiently, cutting down on heating needs. A heat pipe is a tube that conducts thermal energy and contains a working fluid. Condensate is recirculated to the evaporator area thanks to the wrapped screen capillary structure covering the inner wall of the container [1–5]. When a working fluid boils in an evaporator zone and then condenses in a cooler zone, heat is transferred as latent heat energy. Heat pipes may be built to perform a variety of tasks, including temperature regulation, unidirectional heat transfer (thermal diode), and the amplification/diminishing of heat flux, among others, with the right design. When it comes to heat exchange, heat pipes come out on top [6–8].

LITERATURE REVIEW

Zhu et al. focused into the experimental and numerical methods of studying geyser boiling inside a glass THP. A 500 mm long glass tube with an 18 mm ID was used (evaporator: 160 mm, condenser: 180 mm). Water heat exchangers with circulation systems were used to accomplish the heating and cooling. Inside the evaporator section, a geyser boiling phenomenon was captured with a high-speed camera [9–12]. Findings from the CFD simulation and the experiments showed good agreement in the temperature distribution. Even though the geyser boiling was not captured by the high-speed camera, it was well visualised in the simulation.

Kim et al. studied how adding a sintered microporous layer to the THP's evaporator affected its thermal performance. A 935 mm long copper tube was tested in both its vertical and angled configurations (Condenser: 335 mm, adiabatic evaporator: 300 mm, and evaporator: 300 mm). There were 25 mm inside diameter of the tube. Water was employed as the working fluid in FR systems with efficiencies ranging from 25% to 100% and heat fluxes of up to 300 kW/m^2. According to the findings, R_{th} values were reduced by about 51% at FR 35% and about 30% at FR 70%. A 15° to 30° slant from horizontal yielded the highest performance levels [13–15].

Thermal performance of THP with and without a thin, porous copper layer was compared by Solomon et al. The copper THP was just 350 mm in length, 16 mm in diameter on the inside, and 19 mm on the exterior. Each of the three components—the evaporator, adiabatic, and condenser—measured 100 mm in diameter [16–18]. Water containing 30% FR was used to supply heat at varying intensities and angles ranging from 50 to 250 W. The electrochemical deposition process was used to create the porous copper thin layer, which was then used to improve the pool boiling process. They also examined the impact of oxide coatings on thermal conductivity and found that copper provided the best heat transfer.

Eidan et al. studied, using both experiment and simulation, the THP's thermal efficiency. Six different working fluids were used in a THP to compare HVAC system performance: There's R-134, water, ethanol, methanol, butanol, and acetone [19–22]. Power output varied between 20 and 200 W, while the filling percentage went from 40 to 100. The THP was built from a commercially available 400-meter copper tube with a 16-millimeter outside diameter. There was an adiabatic section of 100 mm, an evaporator measuring 150 mm, and a condenser measuring 150 mm. Heat exchangers with hot and cold water jackets were used for the heating and cooling processes, respectively. Within the temperature range of HVAC systems (roughly 30–50 C), water demonstrated its superior thermal performance. When comparing experimental results with those from numerical simulation, there was an agreement of 90% or better.

Fadhl et al. R134a and R404a were used in the Ansys Fluent THP simulations, and the fractional-order (FR) temperature was set to 100%. Between 20 and 100 W of heat input were needed. A 20.8 mm 22 mm 500 mm copper tube was used to construct the THP (adiabatic: 100 mm, condenser: 200 mm, evaporator: 200 mm). It was found that the simulated findings were quite close to the experimental data [23–25].

Heat transfer, pressure, and velocity across a wide range of HP designs were the focus of a suggested universal analytical solution by Lips and Lefevre. Using a Fourier expansion of the thermal and hydrodynamic models, we were able to determine the temperature distributions of the principal heat sources and sinks along the HP [26–30]. The most crucial discovery is that HPs of varying designs can all be predicted in terms of their effective thermal conductivity (thermal resistance) using this method.

In ANSYS/Fluent, Fertahi et al. [19] modeled a THP for a home water heating system using 2D CFD numerical simulation. Copper tubing with a diameter of 20.2 millimeters and a length of 1 meter was used (evaporator length of 400 millimeters and condenser length of 400 millimeters).When it came to pressure-velocity coupling, the SIMPLE method and a VOF model were applied. This problem was solved using a transient method with a time step of 104 s. At the 60-second mark, the simulation stabilized [31–35]. The findings were double-checked against previously published literature, where a high level of agreement was discovered. The authors argued that the THP's thermal performance may be improved by installing slanted fins in the condenser.

The two-phase flow inside a THP was investigated by Temimy and Abdulrasool [15, 16] using both theoretical and experimental methods. The external diameter of the 600 mm long THP copper tube was 16 mm. Lengthwise, it measured 250 mm along the evaporator, 150 mm along the adiabatic portion, and 200 mm along the condenser. The results of the simulation showed a spatial flow pattern that was not constant. To regulate the water vapour and steam vapour streams, they suggested using tube packing (TP) within the THP [36–40]. According to the 3D CFD findings, the THP's performance was improved by lowering the Rth by up to 55% after the TP was inserted, It ultimately resulted in the equal distribution of the two stages.

Alammar et al. [20] is cited for their work in this area. We measured the effect of FR and inclination angle on thermal performance using a THP with an external diameter of 22 mm and an internal diameter of 20.2 mm. Total THP length was 400 mm (evaporator was 200 mm and condenser was also 200 mm). There were three different heat outputs (at 39, 81, and 101 watts) with a wide variety of FR values (from 25 to 100 percent). This research indicates that a FR of 65% is optimal.

Changing the number and size of rectangular longitudinal fins (along the condenser section) can have a significant effect on THP's thermal efficiency, therefore Nair and Balaji ran the numbers to see what would happen. The amount of THP in the condensation was the dependent variable. The THP itself is made from of copper tubing that measures 22 mm on the exterior, 20 mm on the inside, and 500 mm in length. The evaporator and condenser were each 200 mm in length. Aiming to expand the condenser's effective area, the fins were fastened to its inside. The THP itself is made from of copper tubing that measures 22 mm on the exterior, 20 mm on the inside, and 500 mm in length. With eight fins, the data revealed a 22% increase in condensate mass, whereas with 12 fins, the increase was around 32%.

Aswath et al. [2] Water and ammonia were used in CFD simulations to assess heat transfer in solar collectors' vertical evacuated tubes. The entire length of the copper tube utilized was 1800 mm, with the evaporator and condenser each measuring 650 mm in length to achieve a FR of 100%.For the same shape and barrier conditions, they found that ammonia provided superior heat transmission. It was determined that this occurred because ammonia had a lower evaporation temperature.

According to B. Orret et al. Thermoelectric generators and heat pipes have been the focus of research into the car waste heat recovery system [41–43]. There was less heat resistance between the thermoelectric generator and the gas, and less pressure loss in the gas flow, according to the study, because of the heat pipe's smaller fin area. The thermoelectric generator's operating temperature can be modified with the heat pipe's adaptable design. TEG system and temperature control and increase design flexibility.

Ashish A. Wankhead et al. Oil inlet and outlet temperature drops, that is, oil temperature decreases with oil flow. Chintan D. Patel et al. The conclusion is that the active fluid and heat transfer of PHP is significantly higher than that of dry PHP. Due to its low thermal conductivity, PHP's performance in gravity is better than PHP's performance in anti-gravity. Usually, PHP assumes a volume occupancy rate of 40% instead of 80%.

Rahul Royal. Sadly et. al. (2013) This research examines two heat pipes, both of which use ammonia as their working fluid; one has a wick structure, while the other does not [44–46]. Typically, a wick constructed of screen mesh is utilised. In the horizontal plane, the heat pipes are all set at right angles to one another.

Ramesh Ganuga Penta et.al. (2017). Drilling applications that might benefit from heat pipe cooling are the focus of this investigation. The length of the heat input zone, the magnitude of the heat flux being introduced, the depth to which the heat pipe is bored, etc. [47] are all geometrical elements that might affect the effectiveness of a heat pipe. were taken into account to determine the impact of heat pipe drill arrangement.

V.M. Aguiarin et al. (2018) In this piece, we look at the thermodynamic testing findings of a finned thermosyphon used as a heat exchanger. A section of copper tubing was used to create the thermosyphon. As the evaporator's working fluid, water was used, and it was only partially filled (about 40%). When cooling a condenser, forced convection is used (air).

Urmila C. Dhainje, A.G. Kamble In this article, the author draws the following conclusions from research work: Efficiency, flow rate, and total heat transfer coefficient are all related to mass flow rate, and the LMTD falls as the flow rate increases [48]. A compact, efficient and inexpensive device was developed, so a new heat pipe technology with an oil cooler was studied in this work.

Bharat M. Jibhakate, Ph.D., and Dr. M. Basavaraj Bharat Some of the many factors considered by the author in his heat pipe analyses are the container, wick/capillary design, working fluid, tilt angle, and fill ratios. Passive heat pipes can carry heat from an evaporator to a condenser across great distances. How a Heat Pipe Transfers Heat Precisely-The evaporator provides the necessary heat to evaporate the liquid. The fluid then travels to a condenser after being evaporated. Capillary action transports condensate from condenser to evaporator, allowing latent heat in the vapour to be recovered.

KM Stone The author of this study shares his insights into his work with improved heat transfer surfaces in compact heat exchangers. Therein, the origins and basic concepts of heat transport are explored. Finally, some plate-fin enhancement geometries are discussed [49].

Leonard L. Vasiliev Heat pipes, which this article explains, are described, are highly adaptable systems with precise temperature regulation. Micro heat pipes have uses in two-phase thermal control systems and the cooling of electrical components in spacecraft. The most recent developments in the field of heat transmission include sorption heat pipes, loop heat pipes, and pulsing heat pipes. Air is prepared by a heat pipe air preheater in thermal power plants before being heated by the boiler's combustion.

In 2015, Naghavi et al. released a thorough review of hybrid applications. They found that heat pipes combined with latent TES devices for solar applications improved efficiency after studying the experimental literature. The complexity of the equation necessitates the use of both one-and two-dimensional computer simulations, as was highlighted by the numerical studies.

The operational phase is where the entrainment limit, due to the high vapour velocity and low pressure, becomes apparent. It's possible that some liquid droplets will ride back to the condenser on the vapour current. As a result, there is a loss of working fluid and vapour pressure [Kim, 1995]. The evaporator portion dries up after the capillary pressure of the wick is inadequate to make up for the pressure loss of the vapour and liquid [Busse, 1973].

A full heat pipe start and working fluid flow cycle are required for excellent isothermal performance. High-temperature heat pipes undergo a drastic temperature swing during startup, especially when compared to heat pipes operating at medium and low temperatures. Compressibility is especially important in the preliminary stages of production due to the low density and vapour pressure [50]. Once the working fluid temperature reaches the transition point, only then do high-temperature heat pipes reveal their better isothermal quality. High boiling points, latent heats of vaporization, surface tension coefficients, and thermal conductivities make liquid metals like sodium, potassium, and lithium ideal for high-temperature applications like solar receiver systems. When first activating a liquid metal heat pipe, it's crucial to bear in mind the limitations imposed by the sound speed barrier and the viscosity barrier. The only way to improve isothermal performance and heat transmission is to create a continuous flow. The Kundsen number is a measure of the average length of the vapour flow channel, and if the mean free route of the working fluid is much shorter than this value, a continuous flow zone can be established. The reference is: [Tournier, 1996].

Two sets of equations for the transition temperature of the vapour flow zone were provided by Cao et al. and Jang. Since the free molecular flow zone is substantially cooler than the continuous flow zone, a significant temperature increase is seen at the boundary between the two regions. When the starting operation begins, the heat pipe may be seen to split in two, creating a hot zone and a cool zone. With vapor's compressibility in mind, similar results have been found in computational investigations. Thus, the "flat-front" start-up paradigm was presented as a straightforward, one-dimensional alternative [51].

Due to their broad application, heat pipes have been the subject of several synthesis investigations. The wick, the heat pipe's construction, the filling capacity of the working medium, and the pipe's inclination have all been demonstrated to affect the heat pipe's isothermal performance. Figure 1 depicts the processes and influencing elements that affect the isothermal performance of a heat pipe. Heat pipes' thermal performance can be enhanced by using nanofluids, which can boost the working fluid's thermal conductivity and decrease its equivalent thermal resistance [Ramezanizadeh, 2019].

METHODOLOGY

For the purpose of this research on the heat pipe, a 3d modelling software is required to design the pipe with the geometrical parameters such as length of the pipe (l_p), diameter of the pipe (d_p), thickness of the pipe (t_p), radius of the pipe bend (p_d) and height of pipe coil (h_p). Pipes were modeled in 3D using software called CATIA, and their geometric specifications are listed in the (Table 1) below. Different configurations such as straight, L–bend, U–bend, wave and spiral form was considered to design the heat pipe. The heat pipe is then analysed using the FE software, ANSYS to perform the thermal analysis on the designed heat pipe. Different results such as temperature and total heat flux were obtained and displayed in the below sections (Figures 1 to 10) The different configurations were also displayed in the below images.

Different boundary conditions such as heat flow, temperature and film coefficient have been simulated on each pipe and the results were displayed in the following sections. The inputs taken in this research are the pipe inlet maximum temperature of 80°C, the operating temperature is 20°C and the inside film coefficient of the pipe is 100e-6 W/mm^2 ^{0}C and the outside as 30e-6 W/mm^2 ^{0}C. Outputs such as temperature and total heat flux have been determined using the ANSYS software. These images have been displayed in the following sections.

Table 1. Geometrical parameters of the pipe.

Parameter	Value (mm)
Diameter of the pipe	15
Length of the pipe	200
Thickness of the pipe	1
Bend radius of the pipe	30
Height of the pipe	100
Distance between each pipe	60
Pitch of the pipe	20
Helix x coordinate	50

Design of Different Configurations of pipes Boundary Conditions
Design of different configurations of heat pipe such as straight, L, U bend, wave and spiral pipes have been presented in the figure numbers 1 to 5. Boundary conditions and working Temperatures of straight, L, U bend, wave and spiral pipes have been presented in the figure numbers 6 to 10. Temperature contours and heat flux of straight, L,U bend, wave and spiral pipes have been presented in the figure numbers 11 to 20.

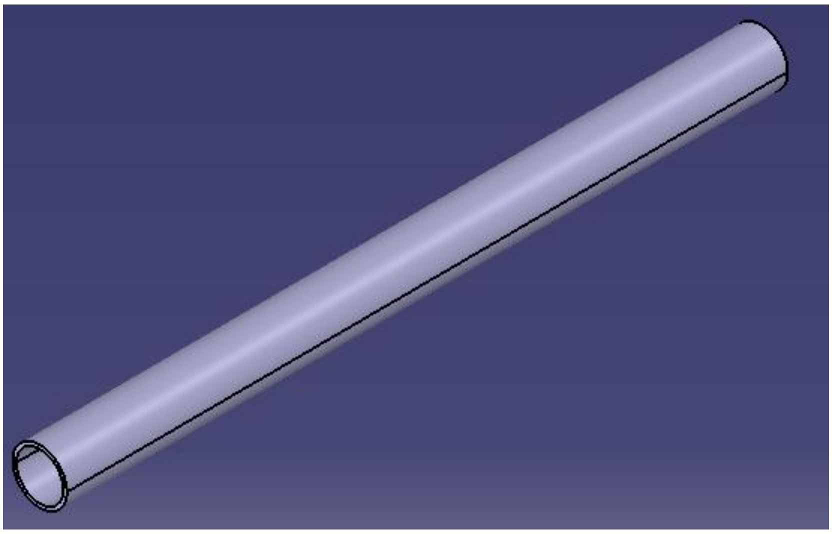

Figure 1. Designed Straight pipe.

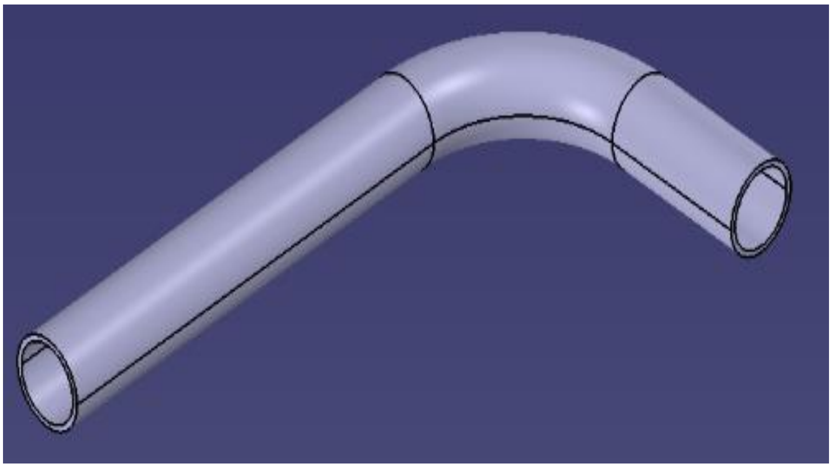

Figure 2. DesignedL–bend pipe.

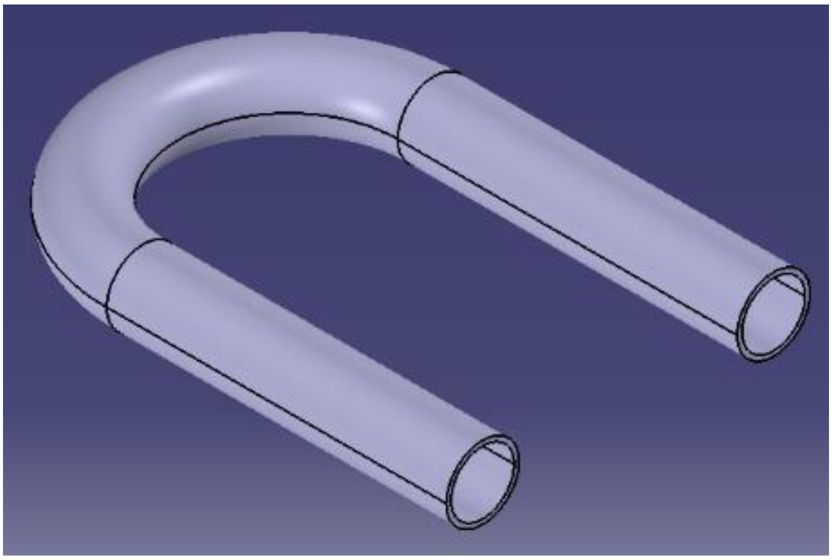

Figure 3. Designed U–bend pipe.

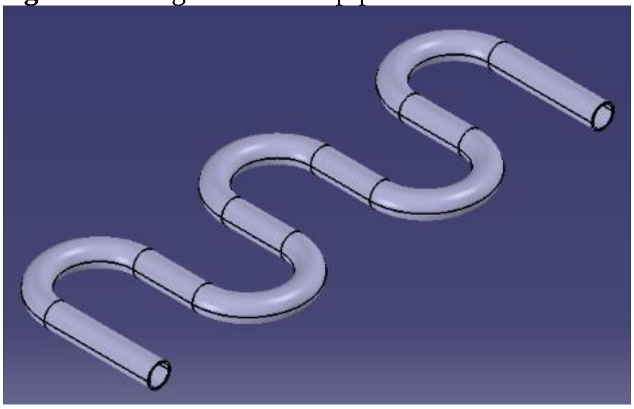

Figure 4. Designed Wave form pipe.

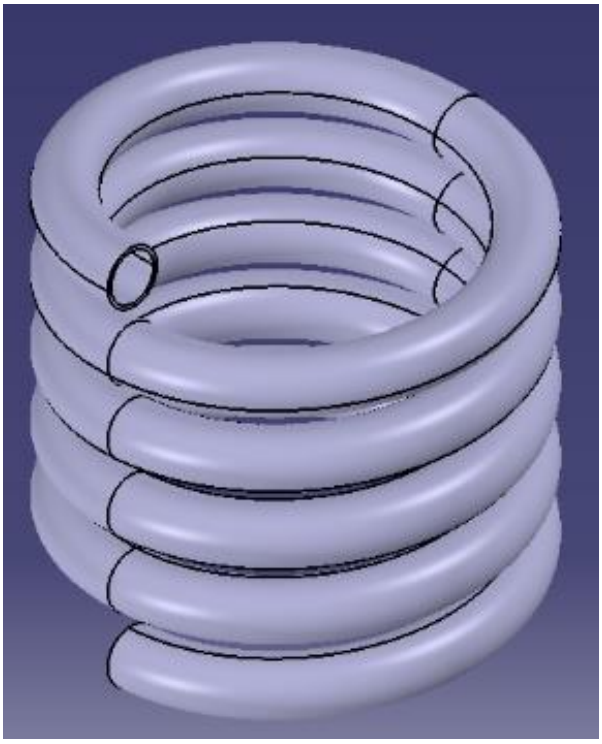

Figure 5. Designed Spiral pipe

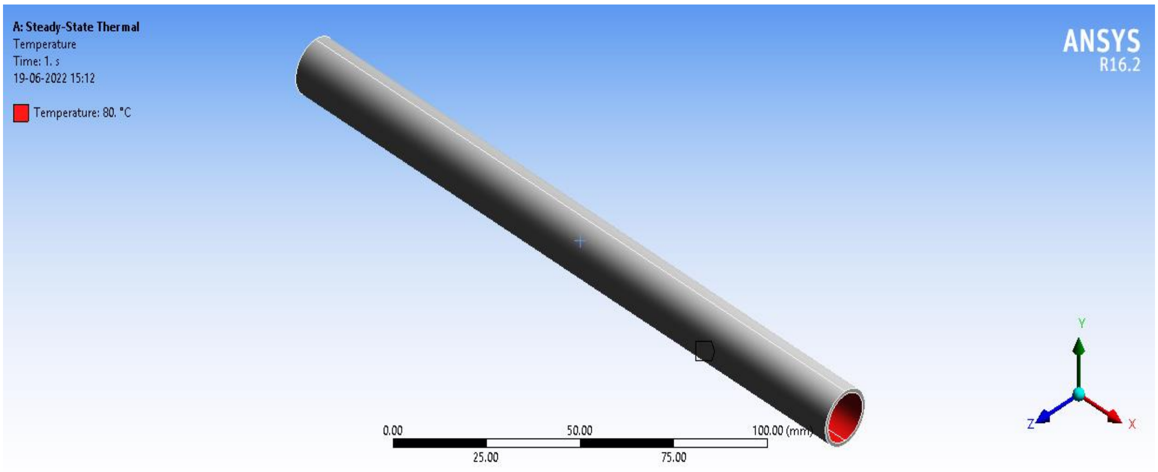

Figure 6. Straight pipe working temperature-ANSYS.

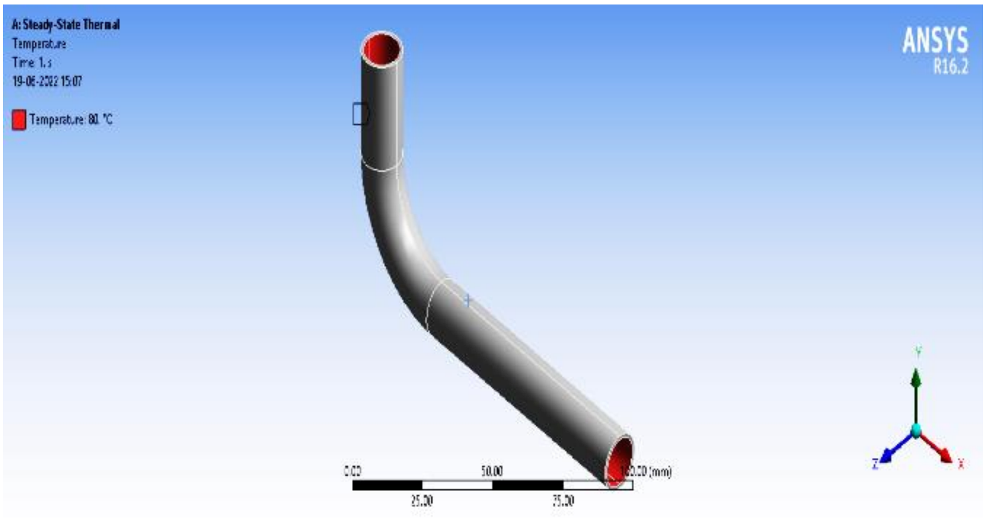

Figure 7. L–Bend pipe working temperature-ANSYS.

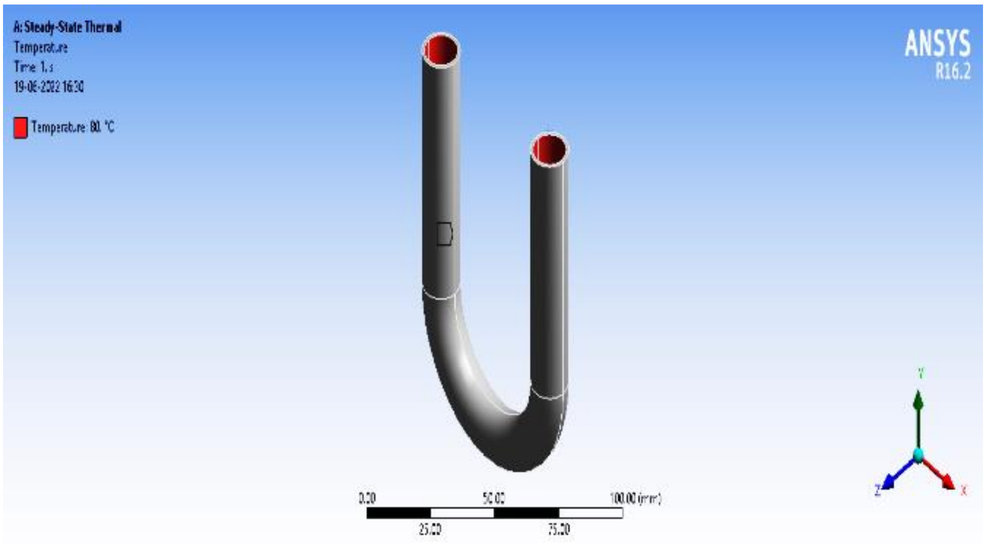

Figure 8. U–Bend pipe working temperature-ANSYS.

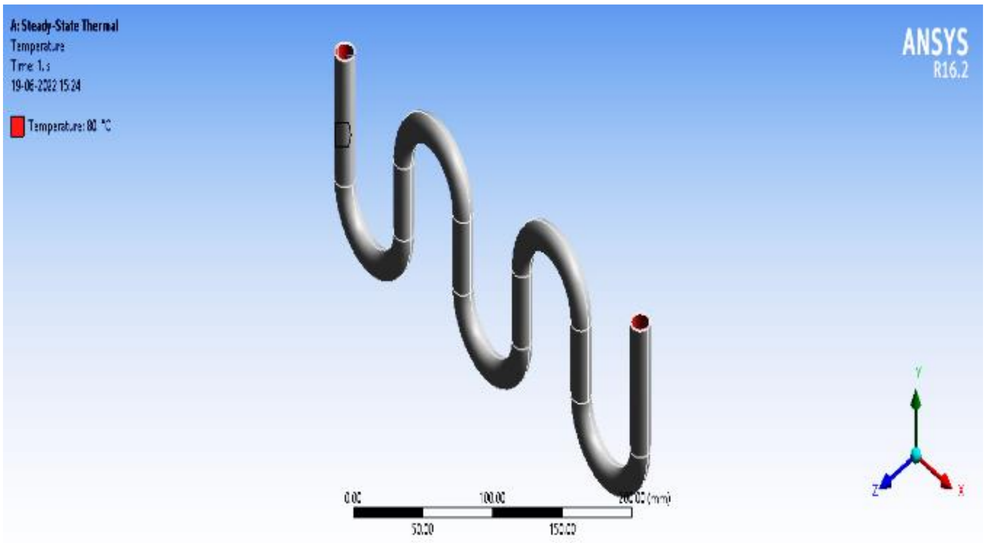

Figure 9. Wave pipe working temperature-ANSYS.

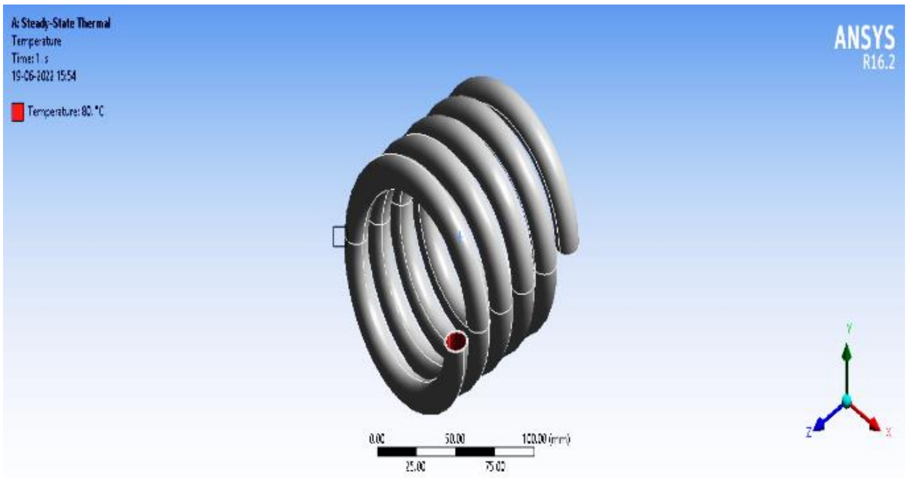

Figure 10. Spiral pipe working temperature-ANSYS.

RESULTS & DISCUSSION

The results indicate that thermal analysis has been performed on the designed heat pipe with different configurations. Outputs such as temperature and total heat flux have been determined for the different pipes. The results indicate that the total heat flux obtained for each pipe is depending on the geometry of the pipe and its configuration. As the straight, l bend, u bend pipe heat flux have only a minute difference in their heat flux generation. The total heat flux generated in the straight pipe is about 0.0020122 W/mm^2 and minimum was found 0.0017309 W/mm^2. Similarly for L – bend, U – bend, wave form and spiral pipe, it was found maximum at 0.0021347 W/mm^2, 0.0021358 W/mm^2, 0.0021561 W/mm^2, 0.11102 W/mm^2 and minimum at 0.0017882 W/mm^2, 0.0017856 W/mm^2, 0.0017635 W/mm^2, 0.00018135 W/mm^2. The results suggest that low heat flux values are obtained for the spiral pipe which are displayed in the below images (Figures 11 to 20) and in Table 1.

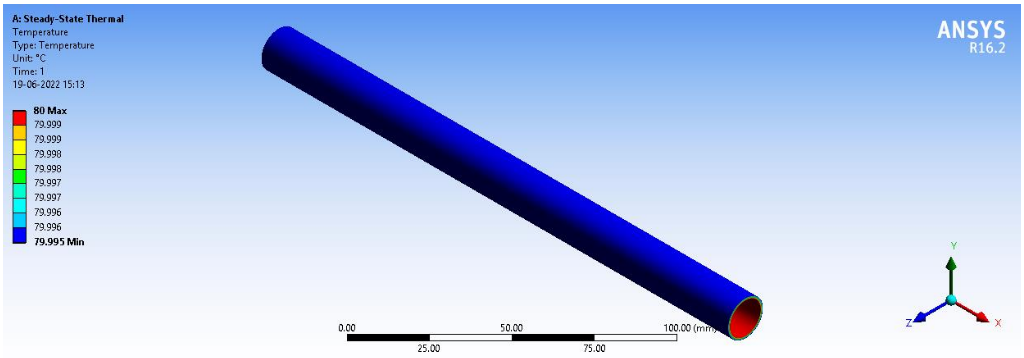

Figure 11. Temperature contour of straight pipe-ANSYS.

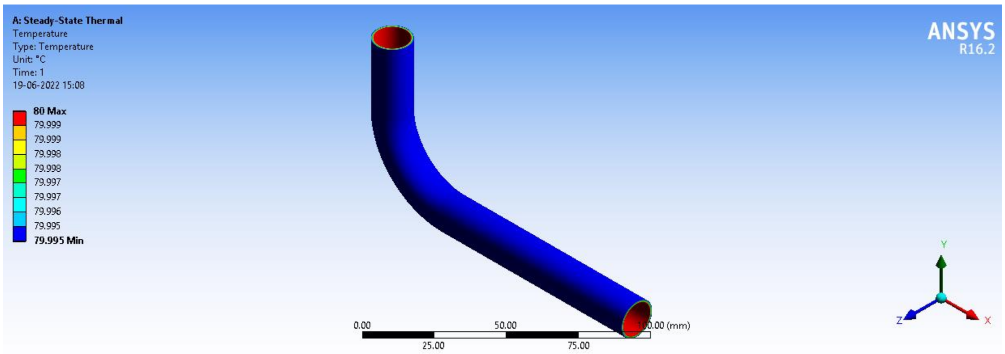

Figure 12. Temperature contour of L–bend pipe-ANSYS.

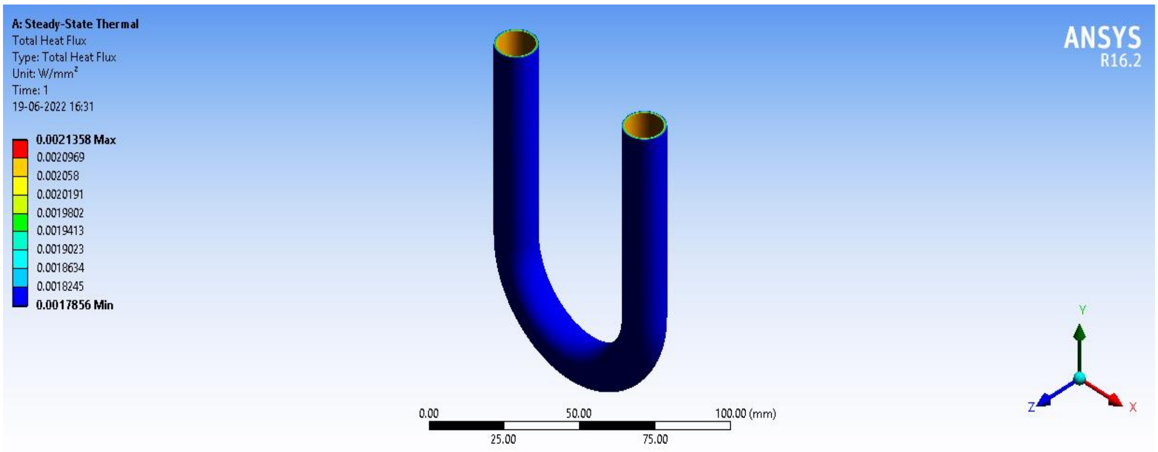

Figure 13. Temperature contour of U–bend pipe-ANSYS.

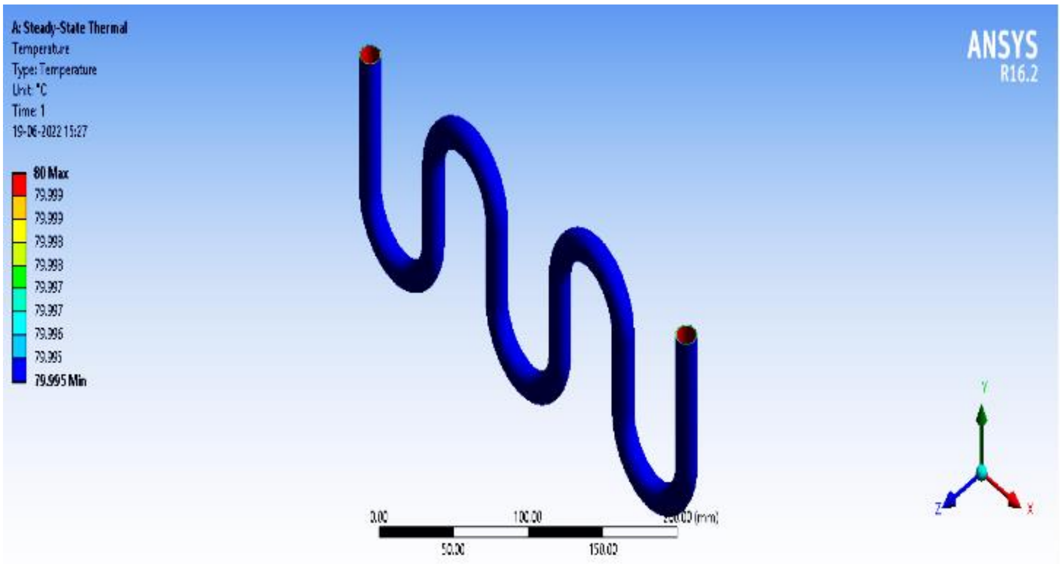

Figure 14. Temperature contour of wave form pipe-ANSYS.

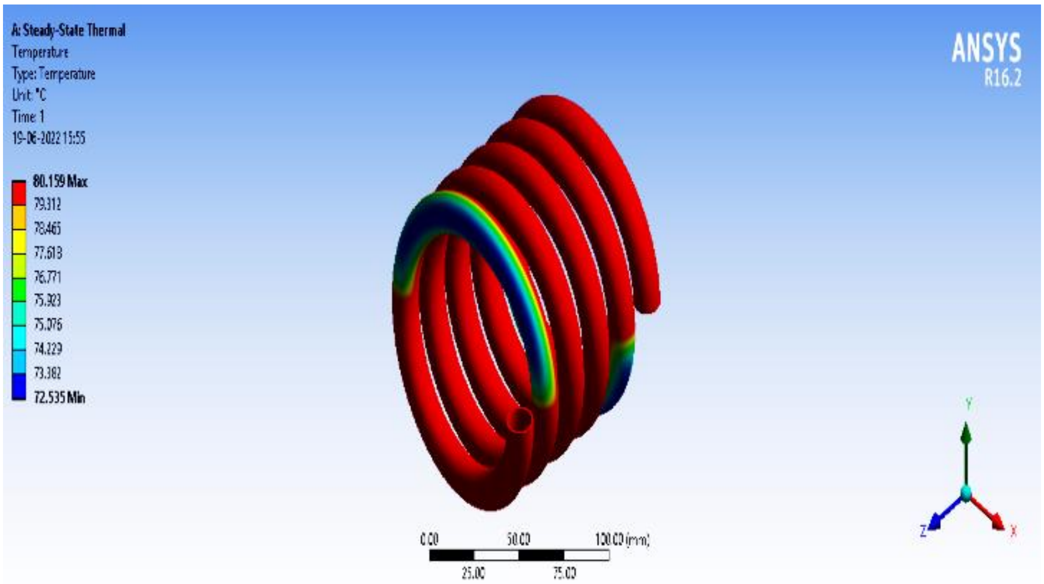

Figure 15. Temperature contour of spiral pipe-ANSYS

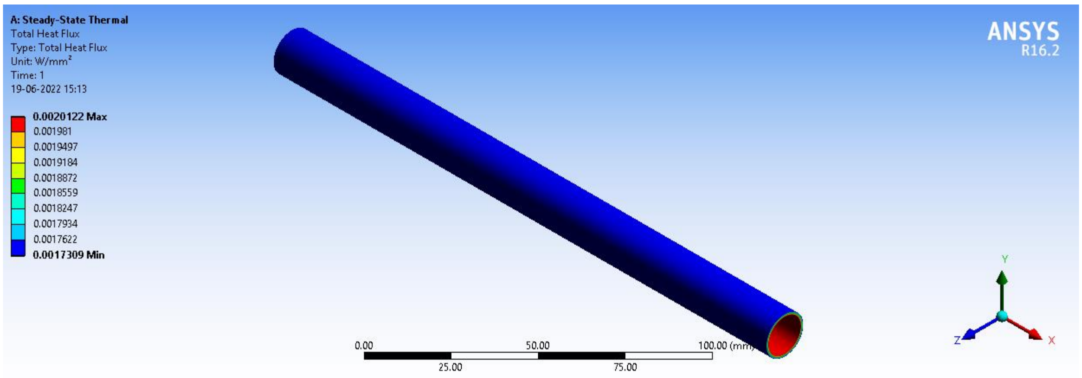

Figure 16. Total heat flux contour of straight pipe-ANSYS

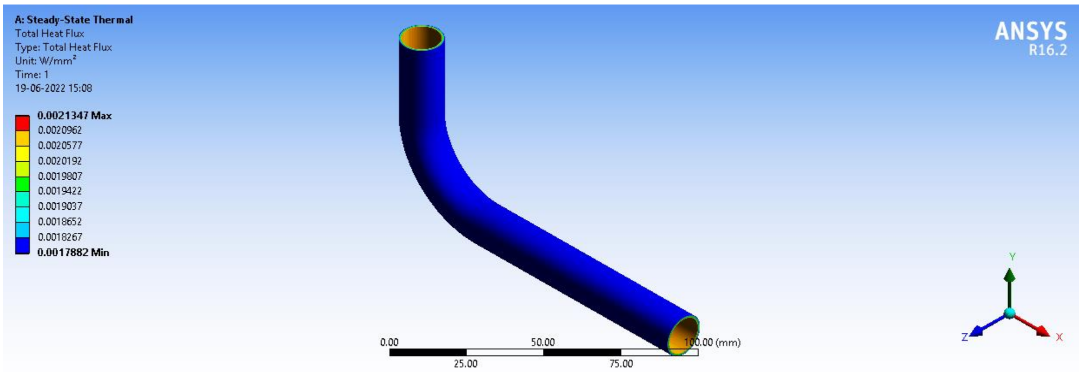

Figure 17. Total heat flux contour of L–bend pipe-ANSYS.

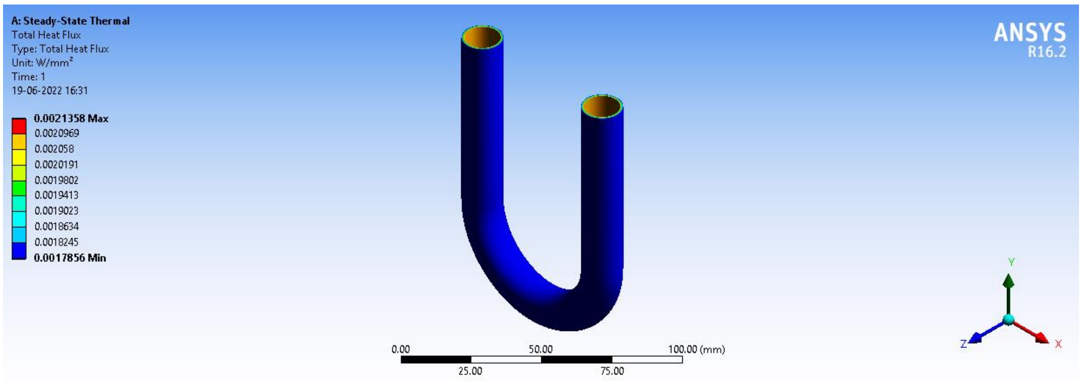

Figure 18. Total heat flux contour of U–bend pipe-ANSYS

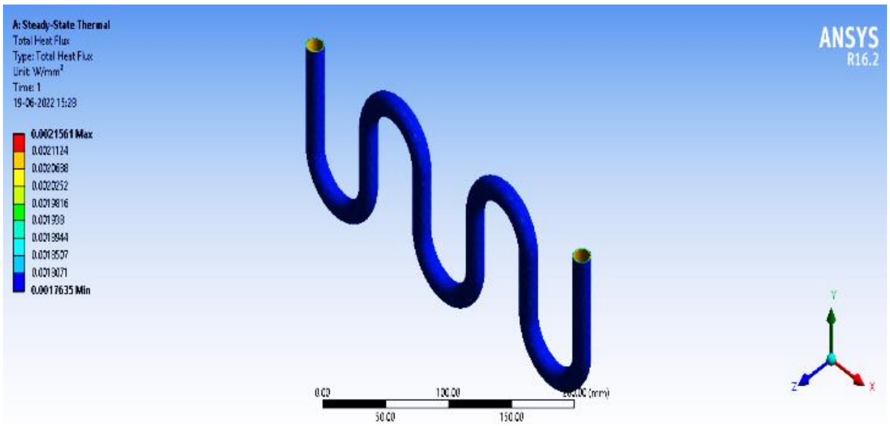

Figure 19. Total heat flux contour of wave form pipe-ANSYS.

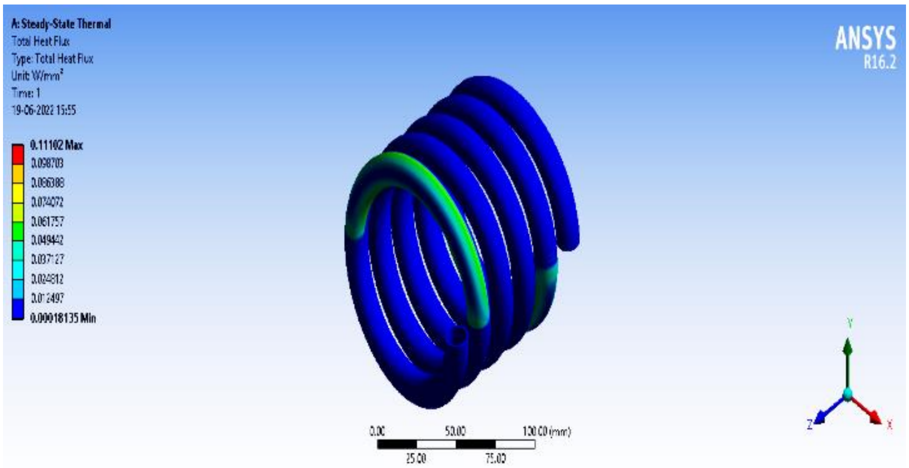

Figure 20. Total heat flux contour of spiral pipe-ANSYS.

CONCLUSIONS

The results for the total heat flux of the different configurations were displayed below with maximum and minimum values. The optimal heat flux was found for the spiral pipe when compare with the other pipe configurations. This indicates the maximum temperature have been found at the spiral pipe only.

Table 1. Heat flux values of different configurations of heat pipe

Type of pipe	Temperature			Heat flux		
	Time [s]	*Minimum [°C]*	*Maximum [°C]*	*Time [s]*	*Minimum [W/mm²]*	*Maximum [W/mm²]*
Straight	1.	79.995	80.	1.	1.7309e-003	2.0122e-003
L – bend pipe	1.	79.995	80.	1.	1.7882e-003	2.1347e-003
U – bend pipe	1.	79.968	80.	1.	1.7856e-003	2.1358e-003
Wave form pipe	1.	79.995	80.	1.	1.7635e-003	2.1561e-003
Spiral pipe	1.	72.535	80.159	1.	1.8135e-004	0.11102

Compliance with Ethical Standards

Conflicts of Interest: The authors declare that they have no conflict of interest. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Ethical Approval: The article has no research involving Human Participants and/or Animals

Competing Interest: The author has no financial or proprietary interests in any material discussed in this article.

DECLARATIONS:

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Availability of data and material: Not data and materials are available for this paper.

Code availability: The data and code can be given based on the request.

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