Design and analysis of grooved heat pipe

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ABSTRACT

A heat pipe is a heat conduction program that utilizes both heat permeability and regime shift concepts to transport heat effectively between 2 different lines. A heat pipe is made up of a pipe or tube and a base fluid. In practice, the heat pipe is poured into a mould that is compatible with the cooling media. These devices have found uses in a variety of fields, including space apparatus, solar energy systems, electronic equipment, and air conditioning systems, due to their simplicity of design and ease of manufacture and maintenance. Thermal performance improvement being the major concern in our project we researched different techniques. The heating surface area has a direct impact on heat transfer. Therefore, we have focused on heat enhancement by introducing grooves. Alongside we also considered using different materials for the pipe. At the end of our research, we are going to produce groove structure models with different materials and analyze them using ANSYS software and propose the best structures with highest thermal efficiency for different applications of heat pipes. This is an attempt to increase heat transmission in response to various material and structural changes. Heat transmission is improved with grooved heat pipes as well as heat transmission varies with different types materials used in heat pipe.

KEYWORDS

heat pipe, thermal conductivity, grooved pipe, porous medium

INTRODUCTION

A heat pipe is a tubular system that uses a metal tube to hold the liquid under pressure and is extremely efficient at transmitting heat. A heat pipe is a tubular system that is very efficient in transmitting heat, using a metal container that holds the liquid under pressure, and the inner layer of the tube is lined with a porous material that functions as a wick [1, 2, 5]. The idea is the same in a heat pipe, which is made up of several wicks. The liquid evaporates into a gas, which travels to the pipe’s cooler before reverting to a liquid and passing through the wick. So, by just using TPCL length, we can see how to optimize the wick shape [3, 4, 9]. We can see how to optimize the filament form just by using the TPCL distance. We know that heat pipes are very efficient at transferring heat, so they are used to allow use of all the thermal superconductor property by allowing for a high heat transfer rate, which allows the device ideal for a more range of applications and industrial works [7, 10, 15]. The inclusion of heat pipes to a variety of temperature scales and applications is a direct indicator of the technology’s ability. The implementation’s economic analysis showed a net annual energy savings of 134 MWh, with a one-month operating payback period (Fig. 1) [6, 8, 11].

We are even aware of the thermal transfer limitations of the heat pipe. There are various constraints on heat pipes, such as the base fluid, the structure of the wick, the dimensions and the temperature at which it is operated. There are also capillary constraints that create...
capillary distinctions around the liquid-vapour interfaces in the inlet and outlet [9, 11, 12]. Similarly, there are other limitations such as sonic limitation, limitation of entrainment, limitation of boiling, and heat pipe performance depends on the heat pipe groove width with grooved capillary structure [13, 14, 16]. All these limitations depend on the fluid properties of the thermos, the parameters of the wick and the heat pipe.

HEAT PIPE DESIGN

There are many factors to consider when building a heat pipe. Material properties, working limit, heat pipe length and diameter, power limitation, heat pipe transport limitation, thermal resistance, heat pipe bending and flattening effects, and operating orientation all receive significant attention [17, 18, 19]. However, by specifying the types of copper/water, the design problems are reduced to a few key considerations. The amount of energy that the heat pipe will bear is perhaps the most major determinant [20, 21, 24, 26]. Another consideration is the temperature range under which the individual working fluid will function. To avoid contaminating the environment or causing a chemical reaction, this working fluid requires a compatible vessel content. Assume that both heat pipes are made of copper and have the same length and diameter of 60 and 3 mm, orderly. The formula is used to measure the rate of heat transfer [22, 23, 25, 26].

The conventional heat pipe: Here is an example of a general heat pipe with a sintered powder wick structure. The heat pipe is depicted in three dimensions below. The inner circle of the heat pipe has a diameter of 10 mm and a length of 200 mm (Fig. 2).

Grooved heat pipe: Using the concept of increasing the surface area, we introduced grooves over the inner walls of the pipe. This wick structure basically not only improves the capillary forces but also increases the surface area which results in increase of heat transfer and overall thermal efficiency of the heat pipe (Tables 1–3, Figs 3 and 4).

METHODOLOGY IN MATHEMATICS

Flow and heat transfer equations that govern flow and heat transmission

The volume of fluid (VOF) technique is utilised when there are particularly in non-source liquids. The stationary and non-stationary circumstances aspect of almost any gas/liquid operating is crucial when the operating liquids functionality is relevant. The scientific formula for the VOF model is similar.

Table 1. Material operating temperature

| Material  | Operating temperature (K) | Operating temperature (°C) |
|-----------|---------------------------|----------------------------|
|           | Foundational | Grooved              | Foundational | Grooved              |
| Aluminum  | 284.35–366.20 | 284.41–414.74    | 11.2–93.05   | 11.26–41.59           |
| Copper    | 283.29–374.37 | 282.41–421.12    | 10.14–101.22 | 9.26–147.97           |
| Steel     | 296.86–313.24 | 295.02–336.19    | 23.71–40.09  | 21.87–63.04           |
Equations of momentum (Navier-Stokes equations)

The mobility formulas in the amount of liquid method, as shown below, are focused on the quantity of densities and friction factor in term of phases weight fractions.

\[
\frac{\partial}{\partial t} (\rho \bar{u}) + \nabla \cdot (\rho \bar{u} \bar{u}) = -\nabla P + \rho \bar{g} + \nabla \cdot \left[ \mu \left( \nabla \bar{u} + \nabla \bar{u}^T \right) \right] + \bar{F}
\]

\[(3)\]

\[
\rho = \alpha_l \rho_l + \alpha_v \rho_v
\]

\[
\mu = \alpha_l \mu_l + \alpha_v \mu_v
\]

where \( F \) is the outside force that acts on the coolants, \( g \) is gravity movement, and \( P \) is pressure.

To compensate for the surface tension effects of cryopreservation, the uniformly distributed force (CSF) approach

\[\sum_{i=1}^{n} \alpha_i = 1 \quad (2)\]
is employed in combination with Black bill’s mathematical model as follows:

\[ F_{cs} = \sum_{pairs,v<j} \frac{\sigma_v (\alpha_{\rho_1} C_v \alpha_1 + \alpha_{\rho_1} C_j \alpha_1)}{(\rho_1 + \rho_2)/2} \]  

(4)

The energy equation in volume of fluid (VOF) form is as follows:

The energy equation in (VOF)

\[ \frac{\partial}{\partial t} (\rho C_v T) + \nabla \cdot (\rho C_v \mathbf{u} T) = \nabla \cdot (k \nabla T) + S_E \]  

(5)

where SE denotes the energy equation’s source term. Thermal conductivity, denoted by \( k \), is computed as follows:

\[ k = \alpha_l k_l + \alpha_v k_v \]  

(6)

The mass-averaged variables, i.e., the energy term (\( E \)), are given by the equation below.

\[ E = \frac{\alpha_l \rho_l E_l + \alpha_v \rho_v E_v}{\alpha_l \rho_l + \alpha_v \rho_v} \]  

(7)

The mass-averaged variables, i.e. the energy term, are given by the following equation (\( E \)).

**Boundary condition**

The condenser portion has a constant wall temperature at thermal boundary conditions, whereas the evaporator has varying heat loads for each filling ratio. The wall motion is stationary in the momentum boundary condition (Fig. 5).

**Meshing**

ANSYS Meshing allows you to specify combinations of point elements, edge controls, surface controls, and/or body controls, giving you additional control. They each have their own set of choices and can be used to change the mesh in a variety of ways. Throughout this scenario, the automatic mesh form approach is applied, but the mesh sizing is done manually. The upper and lower mesh size restrictions are both set to 0.0002 m, as seen in the diagram below. When you use this control level, you will obtain a mesh with 61,1,65 nodes and 5,66,244 elements (Fig. 6).

**Fluent solution setup**

The procedures in this project include setting up the FLUENT solver and simulating the flow. Set up the solver by going to Materials > Selecting a solid and clicking Edit. Use the properties listed in Table 4 to make changes to the solid’s properties.

**RESULTS AND DISCUSSION**

For each variant, various parameters such as density, temperature, and velocity were measured and compared. The effect of the evaporator, adiabatic wall, and condenser temperature are investigated in this simple heat pipe model with water as the heat exchanger and aluminum as the material (Table 5 and Fig. 7).

Conventional copper heat pipe has been analyzed and observed temperatures ranged with a minimum of 284.35 K and a maximum of 366.20 K. The effect of temperature in fluid zone, evaporator, adiabatic wall, and condenser is examined using with water as the heat transfer fluid and copper as the material. Conventional aluminum heat pipe has been analyzed and observed Temperatures ranged with a minimal of 282.41 K and a peak of 374.37 K. The result of temperature in fluid zone, evaporator, adiabatic wall, and condenser is examined using water as the cooling medium and steel as the material. Conventional steel heat pipe has been analyzed and observed in temperatures with a

![Fig. 5. Sequence of applying boundary condition](image-url)
minimum of 296.86 K and a maximum of 313.24 K. The effect of temperature in fluid zone, evaporator, adiabatic wall, and condenser is examined using water as the working fluid and steel as the material (Fig. 8).

Grooved copper heat pipe has been analyzed and observed in temperatures ranged with a minimum of 295.02 K and a maximum of 336.19 K. The effect of temperature in fluid zone, evaporator, adiabatic wall, and condenser is examined using water as the base fluid (Fig. 9).

Table 4. Properties of solid material

| Property                      | Aluminum | Steel | Copper |
|-------------------------------|----------|-------|--------|
| Density (kg m\(^{-3}\))      | 2,700    | 7,790–8,050 | 8,960 |
| Thermal conductivity (W (m\(^{-1}\)·K\(^{-1}\))) | 237      | 54    | 401    |
| Boiling point                 | 2,743    | 700–1800 | 2,835  |
| Molar heat capacity J (mol\(^{-1}\)·K\(^{-1}\)) | 24.2     | 0.466  | 24.44  |

Table 5. Properties of fluid

| Property                      | Value        |
|-------------------------------|--------------|
| Point of boiling              | 100.00 °C    |
| Limited density (at 3.98 °C)  | 1,000 kg m\(^{-3}\) |
| Density (25 °C)               | 99.701 kg m\(^{-3}\) |
| Pressure of vapour (25 °C)    | 23.75 Torr   |
| Vaporization heat (100 °C)    | 40.65 KJ/mole|
| Vaporization entropy (25 °C)  | 118.8 J/K·mol |
| Viscosity                     | 0.8903 Centipoise |
| Surface tension (25 °C)       | 0.7197 Dyn/meter |

A considerable extra heat is deposited on the bottom surface, which would be usually referred to as the liquid desiccant region. The simulation output for the vapour – phase pathway’s evaporated portion is a red outline that turns bluish in the collection region. The speed applicable at the bottom vapour – phase path hugely puts more pressure of warm air at the drying segment, and heat was gradually diffused from the drying stage to the moderate frozen phase at the test section (green contour), and eventually to the coloured curves at the chiller segment. Later, as shown by the blue outline, the heat pipe’s activity has caused the hot fluid to settle (Fig. 10).

Influence of pressure in heat pipe

The overall pressure contour demonstrates that the heat is spread equitably. Because of the green contour of the evaporation portion, the adiabatic section has a light blue contour, and the condensing section has a dark blue contour. The air particles smash smoothly because the container’s surface area is greater than the vapour phase path. Even if the vapour path remains warm, the atmosphere at the container’s interior surface is warm. Because the pressure is not dangerous, the structure does not break or fracture (Fig. 11, Tables 6 and 7).

Influence of temperature in heat pipe

Per the temperature profiles studies, the heat pipe finally implemented heated vapour to trapped moisture. This analysis
proved that somehow a narrow tube with an inherent wick arrangement enables for heating and cooling inside the tube, due to heat transference from the heating to the chilled side. As can be observed, the heat is symmetrical. It shows that the vapour stage has a conductivity, resulting in a high heat flux. The aldol condensation contracts energy in the regenerator, changing it to contracted gas, which would be then turned into a fluid. For its capacity to withstand extreme temps, copper has proven to be a good preference for pipe building projects. Temperature data received at various axial intervals on the heat pipe core is used to construct axisymmetric heat flux. Figure shows the axial temperature field along the heat pipe during a dry run. The graphic depicts the temperature variations in the evaporator, adiabatic section, and

Fig. 7. Temperature distribution in conventional steel heat pipe

Fig. 8. Distribution of temperature in grooved steel heat pipe
condenser because of variations for a dry run. The slope of longitudinal temperature field rises as heat input increases, resulting in higher temperature swings throughout the condenser and evaporator sections, as seen in Fig. 12. A bigger temperature slope is necessary for increased heat transmission in simple conduction heat transfer. In comparison to another category, the copper-water combination HP has $T_{\text{max}}$ at the evaporative section.

Figure 13 depicts the pressure variation in the symmetry plane of a real heat transfer tube. The pressure variations in
the non-grooved model are not nearly as similar as those in the grooved model, as seen in Fig. 13. As the pressure decreases, the dispersion becomes more uniform. Fluid losses grow as the actual heat pipe model includes condenser elements.

Figure 14 depicts the distribution of density drops inside a heat pipe. For the capillary force to push the vapour, the wick’s capillary pressure must be greater than the pressure differential between the vapour and the liquid at the evaporator. The graph also shows that the liquid density lowers.
higher when the heat pipe is operated against gravity. As a result, wick pumping and heat transfer are reduced. The degree of heat transfer reduction is determined by the heat pipe.

Figure 15 depicts the variation in HP's real heat transfer velocity. The exact velocity profile inside of an exact tube's outer tube is primarily the same as before the inside of a purely theoretical pipe's circular area, per this trend line; just one thing that is different is the motion scattering in the internal liquid; the impacts of grippy rubber give flow velocity into the inflatable raft, enhancing the rinsing impacts of the interior layer, and enhancing the heat transfer (Fig. 16).

Table 6. Parameter changes in grooved heat pipe

| S. No | Parameter     | Inlet | Evaporative section | Adiabatic section | Condenser section | Outlet |
|-------|---------------|------|---------------------|-------------------|-------------------|-------|
|       | Water-steel   | 311  | 420.3               | 380.6             | 300               | 287   |
|       | Temperature (K) | 14,680 | 11,809             | 8,817             | 4,499             | 1,680 |
|       | Pressure (Pascal) | 996.2  | 888.6              | 889.2             | 979.2             | 988   |
|       | Density (kg m⁻³) | 0.1    | 1.488              | 1.784             | 2.17              | 2.24  |
|       | Turbulence (m² s⁻²) | 0.057  | 0.15               | 0.513             | 0.724             | 0.799 |
| Water-copper | Temperature (K) | 309   | 421.1              | 391.6             | 322.7             | 312   |
|       | Pressure (Pascal) | 14,640 | 16,620             | 15,100            | 6,042             | 1,510 |
|       | Density (kg m⁻³) | 998.2  | 893.5              | 892.5             | 978.2             | 989   |
|       | Velocity (m s⁻¹) | 0.1    | 0.23               | 0.26              | 0.28              | 0.3   |
|       | Turbulence (m² s⁻²) | 0.05   | 0.158              | 0.334             | 0.490             | 0.5   |
| Water-aluminum | Temperature (K) | 310   | 419.3              | 379.6             | 297               | 283   |
|       | Pressure (Pascal) | 14,569 | 12,910             | 8,606             | 4,303             | 1,430 |
|       | Density (kg m⁻³) | 998.2  | 898.5              | 898.5             | 998.2             | 999   |
|       | Velocity (m s⁻¹) | 0.1    | 1.267              | 1.934             | 2.04              | 2.3   |
|       | Turbulence (m² s⁻²) | 0.06   | 0.12               | 0.468             | 0.689             | 0.8   |

Table 7. Parameter changes in conventional heat pipe

| S. No | Parameter     | Inlet | Evaporative section | Adiabatic section | Condenser section | Outlet |
|-------|---------------|------|---------------------|-------------------|-------------------|-------|
|       | Water-steel   | 309  | 370.3               | 300               | 305               |
|       | Temperature (K) | 14,545 | 10,450             | 9,679             | 9,760             | 9,853 |
|       | Pressure (Pascal) | 995.7  | 978.6              | 989.2             | 997.2             | 999.6 |
|       | Density (kg m⁻³) | 0.1    | 1.634              | 1.784             | 1.19              | 1.37  |
|       | Turbulence (m² s⁻²) | 0.043  | 0.015              | 0.213             | 0.224             | 0.399 |
| Water-copper | Temperature (K) | 310   | 381.4              | 374.6             | 352.6             | 298   |
|       | Pressure (Pascal) | 14,621 | 10,620             | 10,100            | 8,042             | 1,610 |
|       | Density (kg m⁻³) | 997.8  | 894.3              | 894.3             | 988.7             | 989   |
|       | Velocity (m s⁻¹) | 0.1    | 1.73               | 1.88              | 1.99              | 2.10  |
|       | Turbulence (m² s⁻²) | 0.053  | 0.158              | 0.189             | 0.246             | 0.364 |
| Water-aluminum | Temperature (K) | 309   | 382.4              | 368.6             | 317               | 288   |
|       | Pressure (Pascal) | 14,550 | 10,913             | 9,706             | 5,103             | 1,253 |
|       | Density (kg m⁻³) | 999.2  | 897.5              | 898.5             | 998.2             | 999   |
|       | Velocity (m s⁻¹) | 0.1    | 0.267              | 0.934             | 1.04              | 1.1   |
|       | Turbulence (m² s⁻²) | 0.064  | 0.14               | 0.26              | 0.48              | 0.6   |
Because of the propped section, turbulence in grooved heat pipe is slightly higher than in regular heat pipe, resulting in flow limitation. There will be turbulence as a result. The outflow will have more turbulence due to the grooved section. In a conventional heat pipe, the line graph was plotted for aluminum, copper, and steel with their working circumstances. In a grooved heat pipe, the line graph was plotted for aluminum, copper, and steel with their working circumstances. As we can clearly see the difference between the conventional heat pipe and the grooved heat pipe.

Fig. 13. Pressure variation Vs length of HP

Fig. 14. Density variation Vs length of HP

Fig. 15. Velocity variation Vs length of HP

Fig. 16. Turbulence variation Vs length of HP
pipe, we note that the maximum temperature values in the grooved heat pipe are noticeably greater than those in the conventional heat pipe when transmitting heat.

CONCLUSION

The effect of the groove, condensation and evaporation zone material, and cooling temperature on the homologous latent heat and nonlinear thermal of a twisted copper-water, aluminum-water, and steel-water heat pipe was critically examined. It was also investigated how heat and operation circumstances affect the immediate thermal characteristics of a twisty heat pipe. The crucial heat flow increases as the refrigeration temperature rises, but the heat transfer seen between chiller stays relatively consistent. Irrespectively of the chilling degree, the necessary heat flow skyrockets when the size of the exchanger is decreased in half. The rising length influences heat conductivity more than the precipitation area height. When heat is applied to a twisted wire heat pipe, the heats of the evaporate, isothermal, and condensing zones rise in order, after the warmth of the drying oven grows. The heat input is switched off, the twist heat pipe takes longer to recover to its original position than it does at start-up. Heat transfer is also efficient with copper-water combination heat pipes.

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