EXPERIMENTAL INVESTIGATION OF THERMAL PERFORMANCE OF MESH WICK HEAT PIPE USING NANOFUID

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Abstract. In the present world with the advancement in technology and development of devices with high speeds and continuous runs, it has become the most serious challenge to effectively manage the thermal dissipation so that the devices are able to run smoothly and efficiently. With an effective thermal management system, the performance of these equipments or machineries can be improved to a great extent. This can be done by using heat pipes with nanofluids. The suspension of nanoparticles within the size range of 1-100 nm in the base fluids like water, ethylene glycol, etc. is called nanofluid. The aim of this research is to prepare Aluminium-water based nanofluids and to study its various properties. The aluminium nanofluid was synthesised using De-ionized water as the base fluid. The characterisation of the nanofluid was done by scanning electron microscopy (SEM) and transmission electron microscope (TEM) techniques.

1. Nomenclature

1.1 Symbols

\(k_{nf}\) = Thermal conductivity of nanofluid
\(k_b\) = Thermal conductivity of base fluid
\(k_{np}\) = Thermal conductivity of nanoparticles

2. Introduction

Heat pipe technology has become popular for heat dissipation due to its high efficiency. Heat pipe is a thermal transfer device which has capability to transfer heat and energy from one place to another. The rate of this thermal transfer can be 100 times quicker than those of available conventional methods, because of this characteristics they can be titled as thermal super conductors. In addition to the transferring of heat from one region to another, they can also be utilized to isothermalize the temperature distribution.

In a heat pipe, we see 3-sections viz. condenser section, evaporator section and adiabatic section. We allow the object to be cooled to meet with the evaporator section of heat pipe. In this section (evaporator section), after getting heat from the hot body, the working fluid is changed to vapour. The vapour that is formed in the evaporator now travels to cold region from the hot region, the reason for this is pressure difference. Now, at the next section, i.e. condenser section, vapour releases its latent heat and gets condensed to liquid. The working fluid is then returned to the evaporation section either by gravity or capillary action. As we are studying mesh-wick heat pipe, here the working fluid is returned with the help of capillary action.

The heat transfer of liquid can be improved by the inclusion of solid particles into it. After the addition of millimetre or micrometre particles to the liquids, the heat transfer performance did not enhance as
expected due to some constraints such as poor dispersibility, aggregation as well as adhering to inner walls of the setup. To overcome this hindrance, nanofluid was found favourable.

2.1 Applications of Heat Pipe
Aerospace – cooling satellite solar array, Electronics, Medical, Heat Exchangers

2.2 Advantages of Heat Pipe
Very high thermal transfer rate; No maintenance since it has got no moving parts; It can be utilized to isothermalize the space or component; With minimum heat loss, it can be adopted for transmitting heat over a long distance, hereby it allows the separation of heat source from the sink.

2.3 Objectives of The Research
The core purpose of this project is to study the thermal working of mesh wick heat pipe using aluminium oxide nanofluids with base fluid being de-ionized water. The objectives of this study include:
- Characterisation of thermophysical properties of nanofuid
- Determining the augmentation in thermal working of heat pipe using nanofluid

3. Motivation For The Work
In the advancing world, the importance of phase change heat transfer is incredible to the technology. If particularly spoken, heat pipes have emerged as a crucial device that works on the concept of phase change heat transfer. It has a wide range of applications, which may include the energy conservation, space cooling or heating, electronic device/component cooling, etc. Earlier, these systems were equipped with the conventional cooling system, but the performance or capacity of those cooling systems was so low that the devices or systems could not function efficiently during high heat flux operations. As a result, the components failures were seen in a very short time. To get rid of this problem, the heat pipes are equipped to remove the heat efficiently whenever or wherever the high heat flux is developed

4. Literature Review
“Gaugler was the person who introduced the concept of heat pipe in 1942”[1]. He patented the Capillary-based heat pipes. The capillary design was anticipated as the channel for returning the working medium (liquid) from the condenser to the evaporator. According to him, the objective of this invention was “to cause absorption of heat”. In 1963, George Grover individually fabricated capillary-based heat pipes and patented it to term it as "heat pipe". Several types of wick structures were proposed and many working fluids were used. Along with the conventional heat pipes increasing interests are also found now days in the area of flat rectangular /disk type /rotating/flexible/micro heat pipes

Nanofluid is a fluid which contains nanometre-sized (nm-sized) particles, called nanoparticles (typically of the order of 1-100 nm). Nanofluids with increased thermal conductivities are established convective heat transfer coefficients with respect to the base fluids. Previously, different-different base liquids, such as formamide, water etc. have been in use in many heat transfer applications. Many research works have been published by various researchers in this field. The published researches focus on nanofluids containing distinct nanoparticles with different size and volume concentration. Conventional fluids like metallic fluids, ethylene glycol, water etc. were extensively being used in the past as a working fluid [2]. Because of their suspension property, there were some limitations in enhancing the thermal properties.

Sukchana et al. [3] performed an experimental analysis of the effect of R- 134a and the adiabatic length of heat pipe on its heat transfer enhancement. Filling ratio viz. 10%, 15% and 20% and heat flux of the heat pipe from 1.97 to 9.87 kW/m² were varied. The results show that the adiabatic length as much as minimum produced the optimum performance for the filling ratio and heat flux of 15% and 5.92 kW/m² respectively. Bing et al. fabricated and tested the different copper powder size for the micro heat pipe. The method of copper powder pouring and the heat transfer performance of heat pipe was initially analyzed. The copper powder size of 140 – 170 μm sintered at 900 - 950°C registered the best
performance. The authors also noted that the larger wick porosity and the heat transfer capabilities are the important parameters to improve thermal the performance of heat pipe.

Kim et al. [4] performed an experimental work on the effect of the shape of Al₂O₃ nanoparticles dispersed in acetone. The nanoparticles shapes are varied viz. sphere, brick and cylinder and the prepared nanoparticles are suspended in acetone using two-step method. The sphere shaped nanoparticles are enhances the thermal resistance about 33% compared with that pure acetone, whereas the brick and cylinder shaped produce only about 29% and 16% respectively.

5. Characterization

5.1 Method(s) of Nanofluid Preparation

Nanofluids are the mixture of solid particles (basically nano-sized) and the base fluid, but it is not like an ordinary mixture. Many parameters should be considered while the nanofluid preparations i.e., reduced agglomeration and increased stability, chemical aggregation of the fluid and positive/negative energy between the nanoparticles, etc. The nanofluid preparation is the most important step and it is majorly categorized into two groups i.e. Single step or 1-step method and 2-step method.

5.1.1 Single step method

In this method nanoparticles are produced by the evaporation or condensation process. The main drawback of this method is the nanoparticles and the working fluid could not be separated. Akoh et al. [5] developed the single step direct evaporation approach. In this method, nanoparticle size is reduced to its desired level in the base fluid. This method also had the limitation in the separation of dry nanoparticles from the nanofluid.

5.1.2 Two-step method

The 2-step method is commonly used for the preparation of nanofluids. The nanoparticles are separately distributed in the base fluid and then the solution is taken for the ultrasonication. Using the two-step method, Murshed et al. [6] experimentally produced the TiO₂ nanoparticles suspended in water. The authors suggested that the two-step method is suitable for oxide nanoparticles compared with metallic nanoparticles produces less stability. Li et al. [7] utilized the two-step method to prepare the alumina oxide nanofluids. The prepared nanofluid was kept in the ultrasonic homogenizer to avoid the agglomeration of nanoparticles. Preparation of nanofluid by 2-step method is shown in Figure 1.

![Figure 1. Nanofluid preparation by 2-step method](image)

5.2 Equipments used for characterization of nanofluids

The equipments which were used for characterization of nanofluids are SEM, and TEM.

5.2.1 Scanning electron microscope (SEM)

- SEM uses focused beams of electrons to extract high resolution, 3-d images
- For the given sample, it provides information about its Topography, morphology, composition
- Modern SEM can provide a resolution of 1-20 nm
• SEM image of Al$_2$O$_3$ nanoparticles is shown in Figure 2

![SEM image of Al$_2$O$_3$ nanoparticles](image)

**Figure 2. SEM image of Al$_2$O$_3$ nanoparticles**

5.2.2 *Transmission electron microscope (TEM)*

• TEM in present days can be used for studying the defects, composition and layer growth in semiconductors. It can also be used to visualize the grain boundaries, etc. Hence, we can say that the TEM is a very strong and powerful tool for today’s material science lab.

• The TEM works on the basic principles as light microscope works, the difference here is that it uses electrons replacing the light. As we have studied that the electrons wavelength is much smaller than that of light, hence the TEM images resolution obtained is many orders of magnitude better than the image obtained from a light microscope. Thus, we can say that the images obtained from the TEM can show the finest details of internal structure. Figure 3 shows the TEM image of Al$_2$O$_3$ nanoparticles

![TEM image of Al$_2$O$_3$ nanoparticles](image)

**Figure 3. TEM image of Al$_2$O$_3$ nanoparticles**

Table 1 describes the properties of the nanoparticles used in the current study.

| Item           | Description       |
|----------------|-------------------|
| Chemical Symbol | Al$_2$O$_3$       |
| Density        | 3920 kg/m$^3$     |
| Shape of particles | Spherical         |
| Thermal conductivity | 28-37 W/m K      |
| Particle size  | 38-45 nm          |
| Specific Heat Co-efficient | 850 J/Kg K      |

**Table 1. Properties of nanoparticles**

5.3 Thermal Conductivity of Nanofluids
“For a nanofluid, the calculation of effective thermal conductivity can be done using the following equation [8].

\[ k_{nf} = \frac{\frac{k_{np} + 2k_b + (k_{np} - k_b)\varphi}{k_{np} + 2k_b - (k_{np} - k_b)\varphi}} \]

(Eq. 1)

where \(k_{np}\) and \(k_b\) are thermal conductivities of nanoparticles and the base fluid respectively and \(\varphi\) is the volume fraction of the nanofluid.

Table 2. Thermal conductivity of some important solids and liquids

| Component          | Material          | Thermal Conductivity (k) W/m-K |
|--------------------|-------------------|--------------------------------|
| Metallic Solids    | Aluminium         | 237                            |
|                    | Copper            | 401                            |
|                    | Silver            | 429                            |
| Non-metallic Solids| Alumina           | 40                             |
|                    | Silicon           | 148                            |
|                    | Carbon nanotubes  | 3000                           |
|                    | Diamond           | 3300                           |
| Metallic Liquids   | Sodium @644K      | 0.613                          |
| Non-metallic Liquids| Engine Oil       | 0.145                          |
|                    | Ethylene glycol   | 0.253                          |
|                    | Water             |                                 |

The thermal conductivity for the prepared nanofluids was measured at the room temperature for the chosen concentration range of volume and the obtained results have been plotted in the graph shown in Figure 4(a). These values are also plotted with some literature values in the Figure 4(b). In the present work, while analysing the thermal conductivity, there was no unusual improvement in the obtained results but some slight deviations were seen among the literature values. The reasons for these variations maybe – shape and size of nanoparticles, stability method, preparation method adopted for nanofluid preparation and the uncertainties associated with the instruments and experimentation.

![Graphs showing thermal conductivity ratio for Al2O3/D1 water nanofluids as a function of volume concentration and temperature, and its comparison with literature values.](image)

**Figure 4.** Thermal conductivity ratio of Al2O3/D1 water nanofluids (a) as a function of volume concentration and temperature (b) and its comparison with literature values.

6. **Experimentation**

6.1 **Design and specifications of heat pipe**

| Parameter            | Specifications |
|----------------------|----------------|
| Heat pipe material   | Copper         |
| Wick material        | Stainless steel (SS304) |
| Wick type            | Screen wire mesh |
| Evaporator length    | Le : 150 mm    |
### 6.2 Experimental Setup

The setup used for this study is shown in Figure 5. It shows a photographic of the heat pipe setup.

![Photographic view of experimental setup](image)

### 7. Performance Evaluation And Enhancement

$\text{Al}_2\text{O}_3$/DI water nanofluids that have been prepared till now, are now being used as working fluids, with no surfactants, in the modified heat pipe. The functional characteristics of the heat pipe were analysed at different tilt angles and heat inputs. The tilt angles considered for the evaluation are $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ and $90^\circ$ and the heat inputs to the heat pipe were $40$ W, $60$ W and $80$ W. The concentration range of volume % of $\text{Al}_2\text{O}_3$/DI water nanofluid was 0.50% to 1.50%. The temperature of the wall surface in the direction of the heat pipe the length has been plotted at selected heat inputs. The performance of heat pipe has been examined and the obtained values are discussed in detail.

Figure 6 (a–c) shows the variation of wall temperature the heat pipe for $0^\circ$ tilt angle using DI water and $\text{Al}_2\text{O}_3$/DI water nanofluids with the different volume concentration viz., 0.5%, 1% and 1.5% and different heat inputs i.e. 40 W, 60 W and 80 W. After observing the plots carefully, it was observed that the maximum wall temperature was seen for DI water and the minimum wall temperature was seen with 1.5% volume concentration. After increasing the volume concentration from 1% to 1.5%, it was observed that the temperature drop was less than that of 1%.

### Parameters

| Parameter                        | Value          |
|----------------------------------|----------------|
| Adiabatic length $L_a$           | 100 mm         |
| Condenser length $L_c$           | 200 mm         |
| Total length of pipe $L_t$       | 450 mm         |
| Outer diameter of the pipe $d_o$ | 24 mm          |
| Inner diameter of the pipe $d_i$ | 22.6 mm        |
| Thickness of the pipe $t$        | 1.4 mm         |
| Wick permeability $k$            | $3.672 \times 10^{-10} \text{ m}^2$ |
| Mesh size $n$                    | 50 in$^{-1}$   |
| Wire diameter $d$                | 0.041          |
| No of wires/unit $N$             | 2365 m$^{-1}$  |
| No of layers                     | 3              |
| Wick porosity                    | 0.64           |
| Permeability $K$                 | $1.8 \times 10^{-10}$ |
| Aperture size per linear inch    | 17.18          |
| Aspect Ratio (AR)                | 1              |
It was observed that the maximum temperature was seen with DI water and the minimum temperature was seen with 1.5% volume concentration Al₂O₃/DI water nanofluid. Now, these fluids have been taken into consideration for analysis at different tilt angles i.e. 0°, 30°, 45°, 60° and 90°. The wall temperature of the heat pipe with DI water as the working fluid at different tilt angles has been shown in Figure 7.

For all the heat inputs, the optimum tilt angle was found to be 30° as the lowest wall temperature was seen with 30° tilt angle while the maximum temperature was seen with 0° tilt angle.

Figure 6. Wall temperature distributions along the length of the heat pipe for 0° tilt angle, a) 40 W, b) 60 W, and c) 80 W
The wall temperature of the heat pipe at different tilt angles using 1 vol. % \( \text{Al}_2\text{O}_3/\text{DI water} \) nanofluid as the working fluid is shown in Figure 8. For the chosen nanofluid and heat inputs, the optimum tilt angle was found to be 45° as the lowest wall temperature was seen at 30° tilt angle while the maximum temperature was seen at 0° tilt angle.

Figure 7. Wall temperature distribution along the length of the heat pipe using DI water at different tilt angle, a) 40 W, b) 60 W, and c) 80 W

Figure 8. Wall temperature distribution along the length of the heat pipe using 1% vol. concentration of \( \text{Al}_2\text{O}_3/\text{DI water} \) at different tilt angle, a) 40 W, b) 60 W, and c) 80 W

The wall temperature of the heat pipe at different tilt angles using 1 vol. % \( \text{Al}_2\text{O}_3/\text{DI water} \) nanofluid as the working fluid is shown in Figure 8. For the chosen nanofluid and heat inputs, the optimum tilt angle was found to be 45° as the lowest wall temperature was seen at 30° tilt angle while the maximum temperature was seen at 0° tilt angle.
Figure 9 shows the thermal efficiency of the heat pipe for different heat inputs. It was observed that there was a great improvement in the efficiency of the heat pipe when the working fluid was chosen as Al$_2$O$_3$ nanofluid. For the DI water alone, the efficiency was found in the range of 0.6 to 0.69, while for the nanofluid with 1 vol. % concentration this value was greatly improved to the range of 0.71 to 0.79.

8. Conclusions

- The thermal performance of the heat pipe was improved when the conventional working fluid was replaced with Al$_2$O$_3$ nanofluids.
- For DI water, the optimum tilt angle for the heat pipe was found to be 30°, while for 1 volume % Al$_2$O$_3$ it was found to be 45°.
- In accordance with the conclusion #2, it was observed that the optimum tilt angle for the heat pipe is not constant for different working fluids. It showed that the optimum tilt angle is also dependent on the working fluid.
- A good increase in efficiency of the modified heat pipe was observed when Al$_2$O$_3$/DI water nanofluid was used in place of DI water alone.

Future Scope

- The heat pipe performance can be investigated using different wick structure and the results can be used for the optimization of the system.
- Thermal performance of heat pipe can be studied by using the different volume concentrations of nanoparticles and by increasing or decreasing the nanoparticles size.
- For studying the thermal performance of heat pipe, different shapes of nanoparticles can also be used.
- The performance of heat pipes can be studied using different and the latest nanofluids available with better characteristics.

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