Enhancement of the thermal performance of a loop heat pipe using silica-water nanofluid

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Abstract. Loop heat pipes (LHPs) are heat transfer devices which are capable of transferring large amount of heat energy over long distances. This paper presents the results of numerical investigations carried out to determine the effect of silica-water nanofluid on the thermal performance of a LHP. Silica-water nanofluid at 2% nanoparticle concentration and deionised water are considered as working fluids. The power input is varied from 40 to 320 W in steps of 40 W. The numerical results are validated with experimental data available in the literature. LHP using deionised water is used as the baseline case. The results shows that silica-water nanofluid can significantly enhance the thermal performance of the LHP when compared with the baseline case. The evaporator temperature of LHP using nanofluid reduced by 27% than the baseline case. The LHP attained steady state faster (150 s earlier) with the presence of silica nanoparticles due to enhanced thermal properties. Thus silica-water nanofluid based loop heat pipes proves its potential as a suitable working fluid for a wide range of applications.

Keywords : Loop heat pipe; nanofluid; thermal performance; thermal resistance; evaporator temperature

1. Introduction
The loop heat pipes (LHPs) operates on a multi phase fluid flow cycle which is maintained by a capillary medium in the evaporator. It is a heat transfer device which can transmit a large amount of heat over a long distance with negligible temperature difference. In steady state operation these heat pipes have high thermal conductance. Thus, LHPs are also known as super thermal conductors. Their advantages include electricity free operation, no moving parts and ability to work even with small temperature difference and transfer heat energy over long distances with negligible pressure drop [1].

Alekey et al. [2] numerically investigated 3D model of LHP evaporator to analyse the flow and conjugate heat and mass transfer. The simulation results shows that evaporation mainly occurs at the vapour groove corners close to the evaporator. To determine thermodynamic behaviour of LHP a steady state model was developed by Benjamin et al. [3]. They reported the major effect of evaporation coefficient and wick conductivity on the LHP evaporator temperature and its temperature field. Esarte et al. [4] experimentally investigated LHP to develop a new model for cooling diodes which emits high power. It was based on the steady state energy balance equations for each components. The effect of various parameters such as tube radius and length was also studied. Mariya et al. [5] numerically investigated the LHP to develop a 3D model of heat and mass transfer in the flat...
evaporator. The results were used for getting heat exchange dependences of heat load for various orientations of the evaporator. Jobin et al. [6] conducted a review on recent advances on loop heat pipes. It was concluded that investigations based on LHPs using nanofluids were scarce. The thermal performance of LHP using alumina nanoparticles were experimentally investigated by Akshay et al. [7]. It was found that the evaporator temperature can be reduced by 12% using nanofluids than deionised water. Riehl [8] studied the effect of nickel–water nanofluid in a LHP. Result showed that heat transfer coefficient was lower at the evaporator side and operating temperatures were higher throughout the LHP. Masahito et al. [9] also developed a mathematical model to investigate the heat transfer characteristics of evaporator in LHP with a small gap between case and wick. Also the effect of this gap on the thermal properties was discussed. It was found that microgap is an efficient approach for improving thermal performance.

Gunnasegaran et al. [10, 11] conducted experimental and numerical investigations on LHPs with alumina and silica as nanofluids. It was observed that the thermal resistance decreases when using silica-water nanofluid. The LHP charged with alumina-water nanofluid yields lower wall temperature difference between evaporator and condenser and attains steady state faster. Nookarajua et al. [12] experimentally and numerically investigated the thermal performance of LHP using copper sintered wick and compared with deionised water. From the results it can be concluded that as heat input increases the efficiency decreases.

The application of nanofluids in LHP is a challenging and fertile area of research, which is still in its nascent stages. Literature on LHPs are scarce and the use of nanofluids as the working medium in LHPs are scarcer. The present study deals with the numerical investigations on a LHP using silica-water nanofluid at 2% nanoparticle concentration. Heat input ranges from 40 to 320 W in steps of 40 W. The thermal performance of the LHPs using nanofluid is compared with that of deionised water (baseline case).

2. Numerical modelling
A three dimensional model (3D) of LHP is designed as shown in the figure 1. The detailed specifications of LHP is shown in table 1. The simulation is performed in the commercial software package ANSYS.

![Figure 1. Model of LHP used in the present study](image-url)
Table 1. Specifications of LHP used for the numerical analysis

| Specification         | Dimension/material |
|-----------------------|--------------------|
| **Evaporator**        |                    |
| Dimension (mm)        | L45 × W45 × H22    |
| Compensation chamber  |                    |
| Dimension (mm)        | L45 × W38 × H22    |
| Material              | Copper             |
| **Condenser**         |                    |
| Dimension (mm)        | L315 × W96 × H60   |
| Material              | Acrylic            |
| **Vapour line**       |                    |
| Outlet diameter (mm)  | 13                 |
| Inlet diameter (mm)   | 11                 |
| Length (mm)           | 490                |
| **Liquid line**       |                    |
| Outlet diameter (mm)  | 13                 |
| Inlet diameter (mm)   | 11                 |
| Length (mm)           | 490                |

Figure 2. Meshed model of LHP

3. Equations used

During operation, heat input into the evaporator is absorbed by the coated surface of the evaporator and the coated surface of the evaporator will absorb the heat input provided. Part of the absorbed energy will be dispersed back to the ambient while the remaining energy will be absorbed by the heat pipe fluid. This process is expressed as:

\[ Q_e = Q_i - Q_{loss,e} \]  \hspace{1cm} (1)

Where \( Q_e \) = heat absorbed by evaporator and \( Q_i \) = heat input. Assuming the evaporator surface temperature to be \( T_e \), the heat loss \( Q_{loss,e} \) from the evaporator to the ambient is expressed as [13]:

\[ Q_{loss,e} = \frac{\rho \cdot c \cdot \Delta T}{\frac{1}{\sqrt{\frac{x}{c \cdot \rho}}} \left[ \frac{1}{\sqrt{\frac{x}{c \cdot \rho}}} + 1 \right]} \]
\[ Q_{\text{loss},c} = \frac{T_e - T_{\text{amb}}}{R_{\text{amb}}} \]  

(2)

\[ R_{\text{amb}} = \left( \frac{1}{R_{\text{amb}}} + \frac{1}{\sigma \epsilon_e (T_e + T_{\text{amb}}) (T_e^2 + T_{\text{amb}}^2)} \right) \frac{1}{A_e N_e} \]  

(3)

Where \( T_{\text{amb}} \) = ambient temperature, \( A_e \) = evaporator area, \( N_e \) = number/quantity, \( \sigma \) = Stefan Boltzmann constant, \( \epsilon_e \) = emissivity of evaporator, \( h_{\text{amb}} \) = ambient convective heat transfer coefficient and \( R_{\text{amb}} \) = thermal resistance by ambient. The absorbed heat \( Q_e \) is instantaneously taken away by means of the heat pipes loop. This could be achieved by condensation of vapour on the condenser surface and evaporation of liquid in the evaporator section. This part of heat \( Q_{e,c} \) is written as [13, 14]:

\[ Q_{e,c} = \frac{T_e - T_c}{R_e + R_w + R_v + R_f + R_c} \]  

(4)

Where \( R_e, R_w, R_v, R_f, \) and \( R_c \) represents thermal resistance of evaporator, wick, vapour line, and condenser respectively. Since the condenser temperature is high, certain amount of the heat which is transferred to the condenser surface will be dissipated to the ambient. The heat output from the condenser \( Q_o \) is expressed as:

\[ Q_o = Q_c - Q_{\text{loss},c} \]  

(5)

Assuming the condenser surface with the temperature of \( T_c \), \( Q_{\text{loss},c} \) which is the heat dispersion from the condenser to the ambient could be similarly calculated by using equation \( (2) \).

4. Grid independence study and validation
Grid independence study was performed to analyse the influence of mesh density on the numerical results. The maximum evaporator temperature is measured at different mesh densities. Among them four grid sizes were selected considering the variation of obtained results from experimental results available in the literature [10]. The maximum evaporator temperature with different mesh densities are listed in table 2. The maximum evaporator temperature obtained from the present study is 98.15 °C for a mesh with 2,40,514 grid size and that reported in the experimental work is 101.24 °C. So, the grid size corresponding to 98.15 °C is used for further numerical investigations.

| Sl. No. | Grid size  | Maximum evaporator temperature \( ^\circ \text{C} \) | Percentage deviation from the experimental result (%) |
|---------|------------|---------------------------------------------|---------------------------------------------------|
| 1       | 2,01,218   | 107.92                                      | 10.26                                            |
| 2       | 2,40,514   | 98.15                                       | 3.13                                             |
| 3       | 2,79,438   | 104.89                                      | 5.83                                             |
| 4       | 3,08,969   | 103.98                                      | 4.25                                             |

5. Results and discussions

5.1. Effect of heat input on evaporator temperature
Figure 3 represents the effect of heat input on evaporator temperature of LHP using deionised water and silica-water nanofluid at 2% nanoparticle concentration. The heat input is varied from 40-320 W
in steps of 40 W. With the increase in heat input, the evaporator temperature of LHP increased in both cases. But it is lower for LHP using nanofluid. The maximum evaporator temperature obtained by LHP is 172.31 °C and 138.25 °C for deionised water and silica-water nanofluid respectively. About 27% reduction in evaporator temperature can be obtained using nanofluid. It is due to better thermal properties of silica nanoparticles.

![Figure 3. Heat input versus evaporator temperature of LHP](image)

5.2. Effect of silica-water nanofluid on transient temperature distribution of LHP

Figure 4 shows the transient temperature distribution of LHP using deionised water and silica–water nanofluid at 2% nanoparticle concentration. It can be observed the LHP using deionised water is having the highest evaporator temperature. The temperature of all points diminished for LHP when nanofluid is used. This is due to the enhanced thermal properties of silica nanoparticle than deionised water. The LHP takes 800 s to attain steady state when deionised water is used whereas it takes only 650 s to attain steady state when silica-water nanofluid is used.

![Figure 4. Transient temperature distribution of LHP](image)
6. Conclusions
A loop heat pipe was numerically investigated to determine its thermal characteristics using silica-water nanofluid for a heat load of 40-320 W in steps of 40 W and nanoparticle concentration of 2%. The following conclusions are drawn from this work:

1. Evaporator temperature of LHP increases with increase in heat input. But it is lower for LHP using nanofluid than baseline case.
2. Silica-water nanofluid reduced the evaporator temperature of LHP significantly than deionised water. Nearly, 27% reduction in evaporator temperature is obtained.
3. LHP using silica–water nanofluid attained steady state faster than baseline case. The steady state is reached by LHP about 150 s earlier in comparison with the baseline.

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