

Analysis of Miniature Loop Heat Pipe Under Varying Working Fluids and Wick Materials at Low Heat Inputs



V. Murali Krishna and Mechiri Sandeep Kumar

Abstract In modern electronic equipment, the use of heat pipes is steadily increasing as they have maximum heat transport capability per unit area. The driving mechanism in heat pipe is the capillary forces developed in fine porous wick to circulate the fluid. The heat transfer in heat pipe is by both condensation and evaporation. Loop heat pipe is one such kind, which has two-phase heat transfer. In this device, the working fluid is circulated due to surface tension forces formed in wick. It can be operated against gravity and can possess flexible transport lines. In the present work, the performance of loop heat pipe is investigated using different working fluids and wick materials. The results are obtained for low heat input ranging from 5 to 12 W. Results show that acetone fluid had better thermal performance when compared to other fluids as it has very low thermal resistance, which is almost half of the thermal resistance of water. As the heat load increased, the temperature difference also increased between the evaporator and condenser. A better thermal performance was obtained with nickel as wick material.

Keywords Miniature loop heat pipe · Wick materials · Working fluids

1 Introduction

One of the major concerns in several electronics applications, process industries, and power generation is cooling. Cooling can be addressed by selecting an appropriate heat pipe. A loop heat pipe (LHP) is one such device, which possesses a two-phase cooling system with high density of heat dissipation. The quantity of working fluid is fixed, and great amount of heat is transferred by both condensation and evaporation. LHP has the advantage of operating against gravity and higher heat transfer capacity.

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The heat can be transferred to longer distance with least temperature drop. Faghri and Parvani [1] made a numerical study on performance of heat pipe with double wall for various heating as well as cooling loads in laminar flow. An analytical study also conducted to calculate the pressure loss and velocity variation. They observed reverse flow at high rate of condensation. Faghri and Buchko [2] made a numerical and experimental study on heat pipe, to find out the effect of heat load dissemination with several heat sources. An increase in heat capacity was found with rearrangement of heat loads.

Muraoka et al. [3] made both theoretical and experimental study for enhancement of condenser performance by substituting a tube condenser with a condenser having porous wick arrangement. They found substantial betterment in performance. Kaya and Hoang [4] proposed a mathematical model and validated it by performing experiments on two different LHPs for different sink temperatures and heights. They found 5% deviation between theoretical and experimental results. A mathematical model was developed by Muraoka et al. [5] to find the fluid flow and heat transfer characteristics of LHP with porous elements in evaporator and condenser to increase startup stability. An improvement in the performance was noticed compared to their previous work [3]. But effective parting of vapor from liquid was not found due to establishment of liquid layer over the porous element. An analytical model was proposed for looped and un-looped pulsating heat pipes by Shafii et al. [6]. In this model, multiple liquid slugs and vapor plugs were also considered. The heat transport rate enhanced with increase in diameter and also due to temperature difference between heating and cooling walls. They also found that the gravity did not play any substantial effect on the efficiency of un-looped heat pipe.

Kaya and Ku [7] conducted a theoretical and experimental investigation to determine the performance of a small LHP. The parameters considered were heat loads, sink temperatures, and orientations. They observed that with increase in heat load, there was a variation in the working fluid arrangement and increase in pressure loss. A theoretical model developed by Launay et al. [8] to predict the fluid flow and thermal behavior of LHP under oscillating heat loads. The validation of the model was done by experimental data and found a good agreement between them. Qu and Ma [9] conducted a theoretical study to determine the influence of various parameters on startup features of pulsating heat pipe. Their results stated that capillary wall state and kind of working fluid significantly influence the startup characteristics. Kaya et al. [10] made simulation studies to find dynamic behavior of LHP at ambient and vacuum states. They stated that there is a need for empirical correlations at low powers.

Chernysheva and Maydanik [11] performed numerical simulations in a cylindrical evaporator during the startup of LHP. The parameters considered are heat loads, wick materials, and working fluids. They found that the LHP can be started effectively only after formation of vapor from the liquid in the channels. The influence of wick material on the performance miniature heat pipe was deliberated by Singh et al. [12]. They found from their experimental study that the thermal performance of heat pipe was greater with copper wick compared to nickel wick. Kiseev et al. [13] proposed a methodology to design the capillary arrangement for upturned meniscus evaporators

of LHPs. Li and Peterson [14] conducted a theoretical study to investigate the heat and mass transport in a square flat evaporator of LHP with a fully saturated wick. The model developed was precisely predicting the performance of LHP particularly at low heat loads.

Zhang et al. [15] developed a three-dimensional model to investigate fluid flow and heat transfer in the flat evaporator of miniature LHP at the specified heat flux. They found that the heat transfer is less for the fully saturated wick compared to vapor groove inside the sintered wick. Mameli et al. [16] developed non-dimensional heat transfer correlations suitable for different working fluids. The numerical data obtained was validated with experimental data available in the literature for a single loop pulsating heat pipe and found reasonably good agreement. Wu et al. [17] investigated the effect of evaporation surface area on the performance of LHP. Their results indicated that the cooling capability of LHP was increased with increase in surface area. Nishikawara and Nagano [18] developed a mathematical model to determine the effect of micro-gap between the case and wick of the evaporator. The influence of heat load, wick shape working fluid, and wick material on heat transport was studied. They observed an enhancement in heat transfer and reduction in hysteresis of liquid-vapor interface in a porous structure. Recently, Nishikawara and Nagano [19] proposed a model to optimize wick shape in the evaporator of LHPs by using the length of three-phase contact line (TPCL). They observed increase in heat transfer rate up to certain TPCL length, and thereafter, it was decreased due to increase in pressure loss in vapor grooves. It was found that no simulation work is reported in the literature on thermal performance of closed-loop heat pipe at very low heat inputs. Microelectronic devices used in certain applications generate lower heat inputs. So in view of the importance, CFD analysis is made on a miniature loop heat pipe for heat inputs ranging from 5 to 12 W. The heat transfer performance of heat pipe considered was found for five different working fluids namely water, acetone, methyl alcohol, ammonia, and ethyl alcohol. The wick materials considered were nickel and ultra-high molecular weight (UHMW) polyethylene, with fill ratios of 55–85%. Also, variation of evaporator temperature was studied. The loop heat pipe was designed in CATIA V6, and the CFD analysis was made on ANSYS CFD academic research version 19.2.

2 Physical Model

The schematic outline of the loop heat pipe considered is shown in Fig. 1. The evaporator section has a central porous wick through which a volatile working liquid circulates. A reservoir, also called as compensator, is attached on left side of the evaporator tube. The reservoir supplies the working fluid to the evaporator without any interruption. The diameter of porous wick is slightly less than that of the evaporator tube. The space between the cylindrical wick and evaporator tube provides the path for flow of vapor in the evaporator tube. The evaporator tube is exposed to the heat source. The working fluid receives the heat falling on the evaporator tube. The

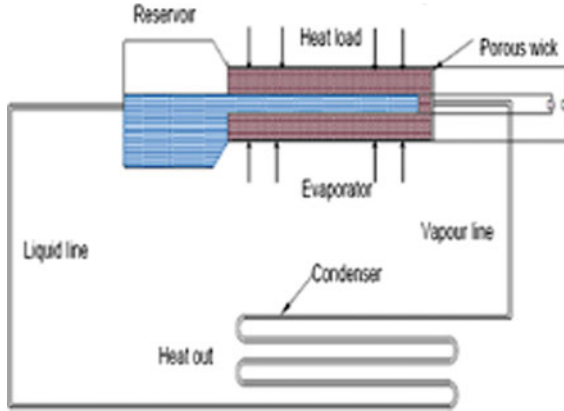


Fig. 1 Loop heat pipe

working fluid in the porous wick vaporizes by receiving the heat, flows through the space between the wick and evaporator tube, leaves the evaporator, and enters into the condenser tube. The condenser section is a coil heat exchanger. Water is circulated over the coil to condense the vapor flowing in the tube. There is a two-phase flow of a mixture of vapor and liquid in the condenser tube. The condensed liquid goes to the compensator from where it is sent to the evaporator tube.

The inner and outer diameters of the copper evaporator are 10 and 20 mm, respectively, and length of the evaporator is 1000 mm. The size of the condenser considered has a coil diameter of 12.5 mm and length 1000 mm. The physical model considered is modeled in CATIA V6 software.

3 Results and Discussion

The model created in CATIA is imported in ANSYS workbench. The model developed is simulated to determine the thermal performance of loop heat pipe considered using Fluent software by applying appropriate boundary conditions. The numerical study is made on the closed-loop heat pipe with five different working fluids and two different wick materials for heat inputs ranging from 5 to 12 W. The fill ratios of 55–85% were considered in the present work, as the heat pipe has better heat transfer performance at lower inputs [20]. The working fluids considered in the present study are water, acetone, methyl alcohol, ammonia, and ethyl alcohol, and wick materials considered are nickel and ultra-high molecular weight (UHMW) polyethylene. The properties of working fluids are listed in Table 1. The heat transfer coefficient (h) is calculated using the equation given below.

$$h = \frac{Q}{A(T_E - T_C)} \quad (1)$$

Table 1 Properties of working fluids at 20 °C

Name	Density (kg/m ³)	Viscosity (mPa s)	Thermal conductivity (W/m K)	Specific heat (KJ/kg K)
Acetone	784	0.306	0.1642	2.15
Ammonia	682	0.138	0.5210	4.74
Ethanol	789	1.150	0.179	2.40
Methanol	792	0.544	0.2040	2.46
Water	998	0.890	0.561	4.18

where Q is the heat input (W), A is the surface area of the evaporator, T_E is the evaporator average temperature ($^{\circ}C$), and T_C is the condenser average temperature ($^{\circ}C$).

3.1 Variation of Heat Transfer Coefficients for Different Working Fluids and Fill Ratios with Nickel as Wick Material

The variation of heat transfer coefficient (HTC) at fill ratio of 55% for working fluids as acetone, ammonia, ethanol, methanol, and water for different heat inputs with nickel as wick material is shown in Fig. 2a. An increase in HTC with increase in heat input for all the working fluids can be witnessed. This is due to improvement of heat transfer rates in condenser and evaporator with increase in heat input. At fill ratio of 55%, the increase in HTC with increase in heat input for water is not significant. The value of HTC increases very gradually with the rise in heat input for water as working fluid, escalates gradually for methanol, ethanol, and ammonia, and escalates very quickly for acetone as working fluid.

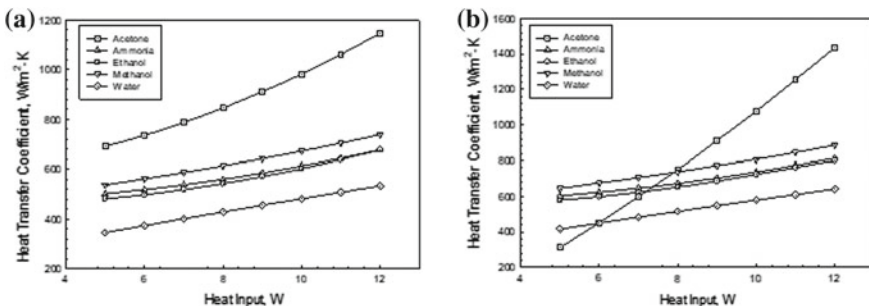


Fig. 2 Variation of heat transfer coefficient with heat input with nickel wick at **a** 55% fill ratio and **b** 85% fill ratio

The variation of HTC with heat input for different working fluids at fill ratio of 85% is shown in Fig. 2b. The values of HTC's escalate with rise in fill ratio for all the working fluids. For 85% fill ratio, the working fluids ammonia, ethanol, methanol, and water display nearly similar pattern of HTC. But acetone shows very high HTC's for greater heat inputs. The repetitive tendency of increasing value of HTC with rise in heat load is restricted by the burn out at maximum heat input. At this state, the amount of condensate coming back is not as much of the rate of evaporation.

3.2 Variation of HTC's for Different Working Fluids and Fill Ratios with UHMW Polyethylene Wick

Metal, ceramic, and plastic materials are used for the preparation of wicks. The thermal conductivity for plastic wicks is very low. The wick with low thermal conductivity enhances the performance of LHP by inhibiting heat transfer from the evaporator to the reservoir section through the wick. So, the numerical results are also obtained with UHMW wick with the same working fluids for different fill ratios and heat loads. Figure 3a. shows the variation of HTC for different heat loads and working fluids at fill ratio of 55%. Among the fluids considered, acetone has maximum value of HTC, and water has least value of HTC. This is due to better flow of acetone compared to other fluids due to low density, surface tension, saturation temperature, and latent heat of evaporation.

As discussed in the previous section, the magnitude of HTC is also enhanced in rise in fill ratio for all the working fluids with UHMW wick. The same can be witnessed from the Fig. 3b. At upper heat loads, acetone has very high HTC's due to quicker bubble creation with enhancement in heat input compared to ammonia, ethanol, methanol, and water.

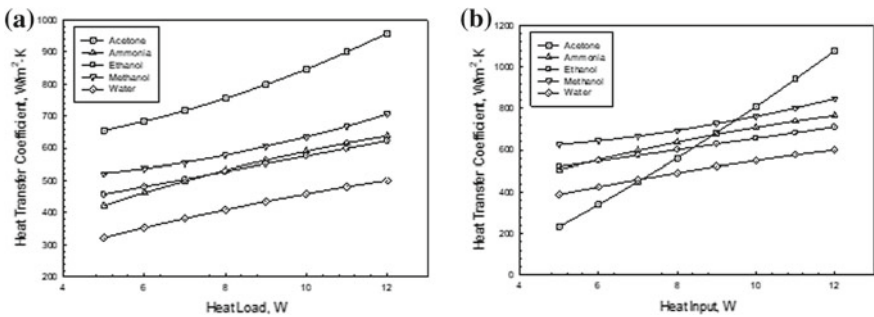


Fig. 3 Variation of HTC with heat input with UHMW wick at fill ratio of a 55% and b 85%

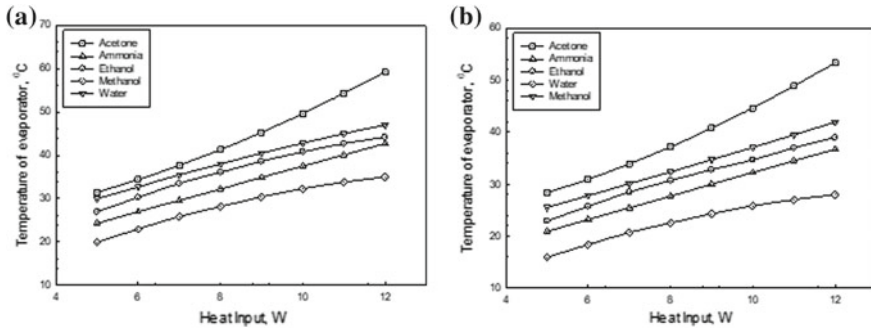


Fig. 4 Effect of heat load on ET at fill ratios of a 55% and b 85% for with nickel wick

3.3 Variation of Evaporator Temperature for Different Working Fluids and Fill Ratios with Nickel as Wick Material

The variation of average steady temperature of evaporator with heat input for acetone, ammonia, ethanol, methanol, and water with nickel wick at fill ratio of 55% is shown in Fig. 4a. The steady-state average temperature of evaporator is enhanced for all the working fluids with rise in heat load. The evaporator temperature (ET) is maximum for acetone and bottommost for water at the steady state. This can be attributed to rapid bubble progression for acetone due to low latent heat of evaporation and saturation temperature. Figure 4b shows the effect of heat load on average ET at the fill ratio of 85%. The working fluids acetone, ammonia, ethanol, methanol, and water displays almost comparable pattern of ET for 85% fill ratio. But the magnitudes of ET are less for all the working fluids due to increase in fraction of the evaporator volume that is occupied by the working fluid.

3.4 Variation of Evaporator Temperature for Different Working Fluids and Fill Ratios with UHMW Polyethylene Wick

The usage of wicks made of UHMW Polyethylene is increasing in heat pipes due to its outstanding machinability and low thermal conductivity. So, the variation of ET with UHMW Polyethylene wick for various heat loads at 55% fill ratio is shown in Fig. 5a from the results attained. The steady-state average ET is enhanced for all the working fluids with increase in heat load. The effect of ET at fill ratio of 85% is depicted in Fig. 5b. The ET is diminished with rise in fill ratio. The constraint of plastic wick is low porosity, which limits the maximum operating temperature.

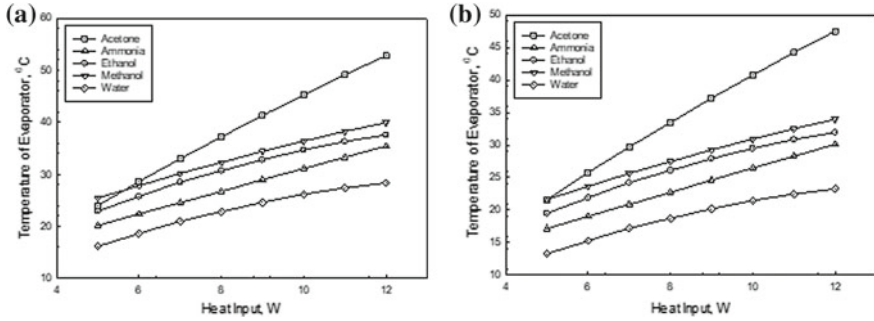


Fig. 5 Variation of ET with heat input for UHMW wick at fill ratio of **a** 55% and **b** 85%

4 Conclusions

In the present work, the heat transfer performance of loop heat pipe was investigated using different working fluids with different wick materials at different heat inputs and fill ratios. It is found that the acetone fluid indicated better thermal performance when compared to other fluids. It is due to the thermal resistance of acetone is very low, which is nearly half of the thermal resistance of water. It was found that as the heat load increases the difference in temperature between the condenser and evaporator also increased. Also found from the results that using nickel as wick material compared to UHMW Polyethylene shows improved performance in terms of heat transfer. It has been observed that the heat transfer coefficient enhances with increase in fill ratio due to decrease in temperature change between the evaporator and condenser, fluids used in loop heat pipe and their specific heat, viscosity, density.

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