Operational Limitations of Heat Pipes with MgO-Water Nanofluid: An Experimental Investigation

Udayvir Singh¹, Naveen Kumar Gupta²

- Department of Mechanical Engineering, GL Bajaj Group of Institutions, Mathura
- Department of Mechanical Engineering, Institute of Engineering and Technology, GLA University, Mathura
- Corresponding author's e-mail address: udayme06@gmail.com

Abstract

This paper presents the study of functional limits of heat pipes with MgO deionized (DI) water nano fluid as working fluid. The nano fluid is made with the help of two step method and it is surfactant free. The output has been analyzed with the increase in concentrations of MgO / DI water nano fluid (0.005%, 0.025% and 0.05%) and at power input of (10 W, 30 W & 60 W), for covering operational range temperature of the electronic instruments. (<60°C). On the basis of the thermo physical properties of the MgO/DI water nano fluid, the functional limits of heat pipe are determined. The changed of working fluids shows an improvement in boiling, pick up (entrainment), viscous and sonic limit except the capillary limit of heat pipe. The surfactant free nano fluids give good safety margin to the boiling limit of the heat pipe, with elimination of chances of locking due to vapor. The capillary limit reduces by the application of nano fluids due to increase in the vapor and liquid flow path resistance rather than capillary pressure in the evaporator section of heatpipe.

Keywords: Nano fluid, Magnesium, heat pipe, boiling limit, Pick up (Entrainment), limit, capillary, limit, sonic limit, viscous limit.

1. Introduction

Thermal management for any device or component includes the heat generation and dissipation at specified rate for effective working of that device. If we consider the example of electronic devices, the heat is a by-product of each electronic device and in general this is disadvantageous for the device, as it affects the performance and reliability of that device. The BCC report about production of semiconductor [1], indicates that the market trend going up for heat exchange devices and may be reach up to $16.3 billion by 2023 from 12.4 billion in 2018 with a compound annual growth rate of 5.6% for the period 2018 to 2023.

The densities of transistors increased from 50 X 10⁴ components per m² in 2004 and may reach up to a million per square centimeter in 2020 [2, 3]. This growth in density of chip together with extremely small size constraint is heads towards the fundamental limit that is why the existing options of heat transfer from the electronic devices have been challenged. The growth in demand of energy efficiency in microelectronics and other appliances with size miniature shows that the effectiveness of heat transfer device is primary factor for effective working of the system[4].

So, it requires developing new cooling techniques for increasing the heat dissipation rates by using the materials which has good thermo physical properties, for the effective operation of the devices under limiting conditions. The heat flow may be increased only by improving the heat transfer coefficient as other heat transfer parameters are constant (surface area, higher and lower temperature limits).

By two phase heat transfer process (Using the latent heat concept i.e., boiling and evaporation process) the heat transfer coefficient can be obtained 10-50 times more as compared to that of obtained by using one state artificial convection process by using same heat transfer medium [5].

A heat pipe [6, 7] is a device in which two phase heat transfer concepts is used. The working fluid absorbs heat by evaporation in evaporator section and this heat is transported to condenser section where the condensation occurs and consequently heat is released. The capillary action is responsible for movement of the working fluid. The main advantage of the heat pipe is its high thermal conductance. By application of heat pipe, higher amount of heat can be transported over a comparatively long length and with relatively low temperature difference [8, 9].
A heat pipe is made of a vessel/container, wick structure and working fluid. The container is divided in an evaporator region, vapor core (adiabatic region), and a condenser region. In evaporator section, evaporation of working fluid takes place by absorption of heat. Due to this a pressure gradient is generated between evaporator and condenser region. This gradient is responsible for movement of vapor through the vapor core to the condenser region. Due to condensation in condenser region heat is extracted and dissipated through an external heat sink. Now due to capillary action the liquid is forced back to evaporator. This capillary action is produced by wick structure. The heat interaction in evaporator and condenser region is considered adiabatic which results negligible temperature drop of vapor.

The nanofluids due to their good thermo physical properties can be used in place of traditions heat transfer mediums in heat pipes [10]. Choi and Eastman [11] first used the nano fluids as working medium to enhance the heat transfer ability of heat pipe. Shafai et al. [12] and Liu et al. [13] analyzed the impacts of use of nano fluids on the output of cylindrical micro grooved heat pipes and concluded that by use of nano fluids as operating medium, there is improvement in output of heat pipe. Nemec et al. [14] justified the operational limitations of heat pipe by using a mathematical model limit. Faghri [15] and Peterson [16] modeled the heat pipes depending upon the different operation limitations and concluded that the limitations are varies with working temperature and thermal characteristics of working fluids. Riehl and Santos[17] studied the working condition of loop Heat pipes with Cu/H$_2$O nano fluids with radius 20 nm  and they justified the improvement in thermal conductivity of working fluid by 15% for a concentration of 5% by mass. Ji et al. [18] practically suggested that heat Transfer performance of oscillating heat pipe (OHP) is improved by the use four different sizes (50 nm, 80 nm, 2.2µm, and 20µm mean diameter) of Al2O3 particles and it depends on the size of particles. Li et al. [19] practically found that by the use of nano fluid in oscillating heat pipe the resistance to heat transfer is lower than that of by use DI water. Alizad et al. [20] observed that the heat pipe performance is improved due to reduction in thermal resistance by application of CuO, Al2O3 and TiO2 nano fluids in flat plate and disc- shaped heat pipe.

Liu et al. [21] investigated that at 45°inclination angles is best by using CuO water nano fluid a concentration of 1.0 % (by weight). Qu et al. [22] found that the use of Al2O3/water nano fluid as working medium in an oscillating heat pipe improves its thermal performance. They found the maximum heat transfer performance with an optimal mass fraction of 0.9 wt. %.

Gupta et al [26] Investigated the effect of heat input (50–150 W), various orientation angles (0°, 15°, 30°, 45°, and 60°), and volumes of the working fluid (20 mL, 25 mL, 30 mL, and 35 mL). The results show that the thermal performance of the heat pipe increases with increase in the heat input until the dry out condition is achieved. The heat pipe achieved the maximum thermal efficiency of 69% at 150 W heat input, 30° inclination angle, and charged with 35 mL of working fluid.

After studying above literature, it is realized that the key design parameters for performance of heat pipe, are heat transfer limitation like capillary, sonic, viscous entrainment, and boiling limits. Peterson [16] investigated that the operational Limits of the heat pipe is mainly influenced by thermal characteristics of working fluid and also varied with the variation in working temperature.
2. Heat Pipe Operational Limits

2.1. Capillary Limit.

The Capability of the capillary to pump the fluid for motion is called capillary limit. It is also called hydrodynamic limit. The pressure head developed by the wick structure is responsible for the movement of the operating medium in the heat pipe. The primary condition for the working of the heat pipe, is that the net head developed by the capillary must be More than or at least equal to the total pressure loss during the flow through the heat pipe.

Thus, the maximum pressure of capillary \( \Delta P_{c_{\text{max}}} \) produced in the region of evaporator in heat pipe,

\[
\Delta P_{c_{\text{max}}} \geq \Delta P_l + \Delta P_v + \Delta P_{pe} + \Delta P_{pc} + \Delta P_g
\]  (2.1)

Where \( \Delta P_l \) and \( \Delta P_v \) are the pressure drops due to inertia and viscosity in liquid and the vapor state, \( \Delta P_{pe} \). \( \Delta P_{pe} \) are pressure drops for phase change in evaporator and condenser portions and \( \Delta P_g \) is pressure drop for gravity during condensate flow.

\[
\Delta P_{c_{\text{max}}} = \frac{2\sigma\cos\theta}{r_c}
\]  (2.2)

Here \( r_c \) = radius of capillary, \( \theta \) = contact angle, \( \sigma \) = surface tension of the working fluid.

For maintaining required flow of working fluid condition given in equation no. 2.2 must be satisfied.

The Capillary limit (\( Q_c \)) is given by

\[
Q_c = 2\left(\frac{\rho_l\lambda\sigma}{\mu_1}\right)\left(\frac{K}{r_{ef}}\right)\left(\frac{A_w}{L_{ef}}\right)\cos\theta
\]  (2.3)

Here \( K \) = Wick permeability, \( A_w \) = Area of wick and \( r_{ef} \) = Capillary radius of wick. \( L_{ef} \) = Effective length of flow passage of liquid and \( \theta \) = Angle of contact (apparent) at interline of evaporator.

2.2. Boiling Limit.

Its other name is heat flux limit. It includes Formation and development or decay of bubbles. The bubbles creation depends on the dimensions and quantity of nucleation spots on boundary of solid. It also depends on temperature gap between the working medium and wall of heat pipe. It is given by

\[
Q_{Bo.} = 2\pi \frac{L_{ef}k_{ef}r_v}{A_v\lambda\rho_v\ln\left(\frac{r_1}{r_v}\right)} \left[\frac{2\sigma}{\left(\frac{r_1}{r_n}\right)} - \Delta P_{c_{\text{max}}}ight]
\]  (2.4)

Here \( r_1 \) = Inside radius, \( r_v \) = Radius of core of vapor and \( r_n \) = Radius of nucleus. \( L_{ef} \) = Effective length of heat pipe and \( k_{ef} \) = Thermal(effective) conductivity of combination of liquid and wick structure.

2.3. Entrainment Limit.

It depends on velocity of vapor. At higher vapor velocity, the shear forces at junction of liquid-vapor may be more than the surface tension forces at the wick. Due to this the droplets of liquid are picked in the vapor flow and will return to condenser. Due to this heat flow, in axial direction is limited. It is expressed as,

\[
Q_{Ent.} = A_v\lambda\left[\frac{\sigma\rho_v}{2r_n}\right]^{\frac{1}{2}}
\]  (2.5)

\[
\Delta P_{c_{\text{max}}} \geq \Delta P_l + \Delta P_v + \Delta P_{pe} + \Delta P_{pc} + \Delta P_g
\]
Here $A_v$ = Area of cross-section of the vapor core and $r_h$ = Pore hydraulic radius of wick surface.

2.4. Sonic Limit.

In heat pipes, the flow area constant and there is variation in velocity of vapor due to evaporation and condensation processes during the flow in heat pipe. The magnitude of velocity of vapor may reach up to sonic velocity or supersonic velocity at a particular condenser temperature of condenser. This may occur at time of start-up or during steady-state operational condition. This limit is given by the following equation:

$$Q_s = A_v \rho_v \lambda \left[ \left( \gamma V \frac{R_v T_v}{2(\gamma V + 1)} \right) \right]^{1/2} \tag{2.6}$$

Here $\gamma V$ = Ratio of specific heat of vapor, $R_v$ = Ratio of universal gas constant and molecular weight of vapor and $T_v$ = Vapor temperature.

2.5. Viscous Limit.

The condition in which vapor gets stationary due to low vapor pressure difference between condenser and evaporator is called viscous limit. It occurs at low operating temperature. In this viscous forces dominate the pressure gradient and consequently the pressure gradient is not able to create the vapor flow. This is also called non-flow condition.

It is expressed as,

$$Q_V = d_V^2 \lambda A_V \left[ \frac{P_v \rho_v}{4(f_v R_v l_d k_v)} \right] \tag{2.7}$$

Where $R_{ev}$ = Reynolds number in the vapor state, $P_v$ = Pressure of vapor

3. Method and Materials

3.1. Preparation of nano-fluid.

Two methods are used for preparation of nanofluids as mentioned:

a. Single step method
b. Double step method

The primary objective of above-mentioned ways is to get a stable and homogeneous nanofluid which can flow without any erosion, collection, and obstruction. In first method the preparation and dispersion of nano particles takes place simultaneously. But in case of double step method the Nano particles are obtained in one step & mixed with parent fluid in the next step.

The material of heat pipe is copper. There is a layer of SS at the external periphery of the heat pipe. The stainless steel is used for coating because:

i. It is good corrosion resistant.
ii. Its durability is good.
iii. Good abrasion resistant.
iv. Very good Ultra Violet protection (maintain its color).
v. Shows good resistance against acids, chemicals, is in comparison of copper.

The heat pipe used here is of 2 cm, outer diameter and of 1.8 cm inner diameter. Its length is 35 cm. For variation in input heat intensity a variable electrical heat source was utilized. This heat source is attached to evaporator side and was in contact with an alternating current source.
An insulator of glass wool is used at evaporator and the adiabatic section. A water jacket is used to supply water for condensation. It has two thermocouples at inlet and outlet sections. These thermocouples are used for measuring condensing water temperature. The resistance against heat flow is expressed as

\[ R_{TH} = \frac{(T_E - T_C)}{Q} \]  

Where \( T_E \) is mean higher temperature, \( T_C \) is mean lower temperature and \( Q \) is heat exchanged between cold and hot sections.

The performance of heat pipe is expressed as

\[ \varepsilon = \frac{Q_R}{Q_S} = \frac{\left( mC(W_{out} - W_{in}) \right)}{VI} \]  

Where, \( \varepsilon \) = effectiveness of heat pipe, \( Q_R \) = Heat released, \( Q_S = VI \) = Power taken, \( m \) = Rate of mass flow of water, \( C \) = Specific heat capacity of the water, \( W_{out} \) = Exit water temperature and \( W_{in} \) = Inlet water temperature

4. **Thermophysical properties of nano fluids.** The nano fluids are used in heat pipes due to their good thermophysical characteristics. These characteristics of MgO/DI water nano fluid are determined by below mentioned expressions.

The density is found by Pak and Cho [23] equation,

\[ \rho_{nf} = \phi \rho_p + (1 - \phi) \rho_b \]  

Where, \( \rho_{nf} \) = Density of nano fluid, \( \phi \) = Volume fraction, \( \rho_p \) = density of nano particle and \( \rho_b \) = density of base fluid

The constant pressure specific heat is calculated by below mentioned equation given by Xuan and Roetzel [24] as follows:
Where,

\[
(\rho C_p)_{nF} = \text{Nanofluid heat capacity} \quad (\rho C_p)_p = \text{Nanoparticle heat capacity}, \quad \phi = \text{Volume fraction} \quad \text{and} \quad (\rho C_p)_b = \text{Base fluid heat capacity}.
\]

Viscosity and thermal conductivity are measured using following equations given by Godson, L, Raja [25]

\[
\frac{\mu_{nF}}{\mu_b} = (1.005 + 0.497\phi - 0.1149 \phi^2) \quad (4.3)
\]

\[
\frac{k_{nF}}{k_b} = (0.9692 \phi + 0.9508) \quad (4.4)
\]

Here, \(\mu_{nF}\) = Viscosity of nano fluid, \(\mu_b\) = Viscosity of base fluid, \(k_{nF}\) = Thermal conductivity of nano fluid and \(k_b\) = Thermal conductivity of base fluid.

5. Result and Discussion:

The results show that the heat pipe operation is affected by the all five limits and volume concentration as discussed below.

5.1. Entrainment Limit.

In this limit, the variation of heat transport capacity with average temperature of operation is shown in plot 5.1. It indicates that the heat transfer capacity of heat pipe is increases with increase in the volume concentration of the magnesium oxide nano particles in DI water. The entrainment limit value is improved with the increase in the dependent variables with the variation in operating temperature and volume concentration. Also, this limit tries to achieve a fixed value with the enhancement in the operating temperature on further increase in concentration of nano fluid.

![Fig. 5.1 Entrainment limit of heat pipe using MgO/DI water nano fluids](image-url)
In this limit, the variation of heat transfer capacity as a function of average operating temperature is shown in graph 5.2. The vapor velocity can be reached up to sonic or super-sonic value in the evaporator region, during its motion in the vapor core of the heat pipe. It is clear from the plot 5.2 that by application of nano fluids, there is increment in sonic limit if the mean operating temperature is increases.

Fig. 5.2 Sonic limit of heat pipe using MgO/DI water nano fluids

5.3. Viscous Limit.

The variation of viscous limit with respect to average temperature of operation shown in diagram 5.3. There is increase in viscous limit if the concentration of nanofluid increases. This enhancement in the viscous limit of working fluid will remove the limitation of working with larger heat pipes, at a temperature near to melting point of working fluids.

Fig. 5.3 Viscous limit of heat pipe using MgO/DI water nano fluids
The variation of boiling limit is shown in figure 5.4. The boiling limit improves by the use of nano fluid in the heat pipe. It improves with the increase in nanofluid concentration and if the mean operating temperature increases this limit decreases.

![Boiling limit graph](image)

Fig. 5.4 Boiling limit of heat pipe using MgO/DI water nano fluids

5.5. Capillary Limit.

If volume concentration of nanofluid increases the capillary limit decreases and if the mean operating temperature increases this limit also increases.

![Capillary limit graph](image)

Fig. 5.5 Capillary limit of heat pipe using MgO/DI water nano fluids

6. Conclusion. By the application of MgO and DI water nanofluid, the variation of heat pipe operational limitation and effect on performance presented in this study. It is found that by the application of MgO nano particles with concentrations of 0.005%, 0.025% and 0.05% operating limitation are increased in comparison
Performance and range of operation is improved due to enhancement in these limitations. The dry out problems in evaporator is also reduced. It’s also found that the value of capillary limit is different among the different limits of heat pipe. The heat fails to operate beyond this limit, the heat pipe fails due to the incapability of the wick structure for supplying required amount of working fluid to the evaporator.

References:

[1] McWilliams A. The market for thermal management technologies”, BCC Research Report Code SMCO24J, 2014.
[2] Gordon E. Moore, Cramming more components onto integrated circuits”, Electronics, pp. 114- 117, 1965.
[3] Abraham V. and Iyer G., Semiconductor Industry: Rising up the value chain”, Wipro council for Industrial Research, 2012.
[4] Saucie I., Akbarzade A., Johnson P., Chracteristics of two-phase closed thermosyphons for medium temperature heat recovery applications. heat Recovery Systems and CHP. 1995; 15(7): P. 631-640.
[5] Khandekar S., Groll M. and Luckchoura V., An introduction to pulsating heat pipes”, Electronics Cooling Magazine, vol. 9, no. 2, pp. 38-41, 2003.
[6] Grover, G.M. US Patent 3229759. Filed 1963.
[7] Grover, G.M. Cotter, T.P. and Erickson, G.F. Structures of very high thermal conductance. J. App. Phys.1964; Vol. 35. P. 1990
[8] Firouzfar E., Attaran M., A review of heat pipe heat exchanger activity in Asia, Proceedings of world academy of science, engineering and technology. 2008; 30:1307- 6884.
[9] Gaugler, R.S. US Patent 2350348. Appl. 21 Dec, 1942. Published 6 June 1944.
[10] Gupta, N. Tiwari, A, Ghosh, S, 2018 vol: 90
[11] Choi, S. U. S., and Eastman, J. A., 1995, “Enhancing Thermal Conductivity of Fluids With Nanoparticles” the ASME International Mechanical Engineering Congress and Exhibition, San Francisco, CA, pp. 99-105.
[12] Shafai, M., B Bianco, V., Valais, K., and Manca, O., 2010, “An Investigation of the Thermal Performance of Cylindrical Heat Pipes Using Nanofluids,” Int. J. Heat Mass Transfer,53, pp. 376-383.
[13] Liu, Z. H., Li, Y., and Bao, R., 2011, “Composite Effect of Nanoparticle Parameter on Thermal Performance of Cylindrical Micro-Grooved Heat Pipe Using Nanofluids,” Int. J. Thermal S, ci.,50 pp. 558-568.
[14] Nemec, P., C Raja, A., and Malcom, M., 2011, “Mathematical Model for Heat Transfer Limitations of Heat Pipe,” Math. Compute. Model., 57, pp. 126-136.
[15] Faghi, A., 1995 THeat Pipe Science and Technology Taylor and Francis Publication, Washington, DC.
[16] Peterson, G. P., 1904, An introduction to Heat Pipes, Modeling, Testing and Applications, Wiley-Interscience Publication, John Wiley and Sons, New York.
[17] Riehl, R. R., and Santos, N. D., 2012, “Water-Copper Nanofluid Application in an Open Loop Pulsating Heat Pipe,” Appl. Therm. Eng.,42, pp. 6-10
[18] Ji, Y., Ma, H., Su, F., and Wang, G., 2011, “Particle Size Effect on Heat Trans-fer Performance in an Oscillating Heat Papeete. Therm. Fluid Sci.,35 (4), pp. 724-727.
[19] Li, Q. M., Zou, J., Yang, Z., Duan, Y.-Y., and Wang, B.-X., 2011, “Visualization of Two- of the Staring Characteristics of Flat-Shaped Heat Pipes Using Nanofluids,” Int. J. Heat Transfers 5 (1—3), pp. 140-155.
[20] Alizad, K., Vafai, K., and Shafahi, M., 2012, “Thermal Performance and Opera-tional Attributes of the Startup Characteristics of Flat-Shaped Heat Pipes Using Nanofluids,"Int. J. Heat Mass Transfer,55 (1–3), pp. 140–155.
[21] Liu, Z. H., Li, Y. Y., and Bao, R., 2010, “Thermal Performance of Inclined Grooved Heat Pipes Using Nanofluids,” Int. J. Therm. Sci.,49 (9), pp. 1680— 1687
[22] J Qu, J., Wu, H. Y., and Cheng, P., 2010, “Thermal Performance of an Oscillating Heat Pipe With Al2O3 Water Nanofluids,” Int. Commun. Heat Mass Transfer,37 (2), pp. 111-115.
[23] Pak, B. C., and Cho, I. Y., 1998, “Hydrodynamic and Heat Transfer Study of Dispersed fluids With Sub-Micron Metallic Oxide Particles,” Exp. Heat Transfer, 11, pp. 151-170.
[24] Xuan, Y., and Roetzel, W., 2000, “Conceptions for Heat Transfer Correlation of Nanofluids, ” Int. J. Heat Mass Transfer, 43, pp. 3701—3707.
[25] Godson, L., Raja, B., Lal, M. D., Wongwises, S., 2010, “Experimental Investigation of Thermal Conductivity and Viscosity of Silver-Deionized Water Nano-fluid,” Exp. Heat Transfer,23 (4), pp. 317-332
[26] Gupta, N, Tiwari, A, Ghosh, S, 2018 vol: 90 “Experimental Investigation of Thermal performance of mesh wick heat pipe” Heat Transfer Research, 49(18), pp.1793–1811.
