Journal of Material Science and Mechanical Engineering (JMSME)
p-ISSN: 2393-9095; e-ISSN: 2393-9109; Volume 3, Issue 3; April-June, 2016 pp. 243-249

http://www.krishisanskriti.org/Publication.html

Analysis of Heat Transport Limitations and Heat Transfer Coefficient using (Al_2O_3- water) Nano Fluid inside Axially Grooved and Sintered Wick Copper Heat Pipe

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Abstract—*Heat pipes are two phase passive heat transfer device with minimum thermal gradient and losses used in various applications such as electronic cooling defence cooling and space applications in the range of (293-473K). In this paper mathematical and theoretical analysis of heat transport limitations and heat transfer coefficient is done using (Al_2O_3- water) Nano fluid inside Copper Heat Pipe under the operating temperature range of (293-343K).Analysis shows that there is enhancement in heat transfer coefficient inside the heat pipe of axially rectangular grooved wick of about 7.33% as compared to water as a working fluid and that of 10.91% when sintered copper wick is used instead of axially rectangular grooved wick in the copper heat pipe. Comparison between heat transport limitations is done using Nanofluid and water as the working fluid with both axially rectangular grooved wick and sintered wick inside copper heat pipe with volume fraction is taken as 1%*

Keywords*: Heat pipe, Nano fluid, Heat transfer coefficient, Heat transport limitations, axially rectangular grooved wick, Sintered wick*

1. INTRODUCTION

With the increase of work frequency and heat flux of electronic components, the dissipation problem of the high heat flux components becomes one of the key technologies of the electronic device design, there is an urge of increase rate of heat transfer coefficient inside the heat pipe thereby by improving the thermal performance of heat pipe and solving the high heat flux dissipation problem to some extent Up to now, heat pipe technology has been widely applied in the field of microelectronics cooling, as the improved construction of the general heat pipes , flat heat pipe has now become a hotspot technology of heat pipe research and development and has been widely applied in many fields, such as spacecraft thermal control, high heat flux electronic cooling. All of the heat pipes, including conventional heat pipes, flat heat pipes and micro heat pipes have common problem of heat transfer limitation[3]. These limitations determine the maximum possible heat transfer rate for a particular heat pipe under normal working conditions. The various limitations of the heat pipe are continuum flow limit, frozen startup limit, viscous limit, sonic limit, entrainment limit, capillary limit, condenser limit and boiling limit (Chi, 1976; Faghri, 1995; Sonan, 2008)[2]. Among them the capillary limits and boiling limits are important for heat pipe design and operation. The surface tension is an important key factor for capillary limit along with boiling limit, sonic limit, entrainment limit, viscous limit and condenser limit. These heat transfer limitations also depend upon the working fluid, the type of wick structure and the heat pipe operational temperature. The working fluid that we are using in heat pipe must have good thermal stability properties at the specified operational temperature. Working fluid must have high surface tension and other desirable thermo-physical properties include a high liquid thermal conductivity, high latent heat of vaporization, low liquid viscosity, and a low vapor viscosity. Therefore, the working fluid must be chosen to take into account operating temperature(293-343K) and also its chemical compatibility with the container and wick materials because the wick structure and working fluid generate the capillary forces required to pump liquid from the condenser to the evaporator and keep liquid evenly distributed in the wicking material.

Several experimental study have been proposed but not much theoretical analysis have been done till date to calculate the Heat transport limitations using nanofluids at different concentration.

In this paper mathematical and theoretical analysis of heat transfer coefficient is done using (Al_2O_3- water) Nano fluid inside copper heat pipe with axially rectangular grooved wick and sintered copper wick under the operating temperature range of (293-343K).Comparison between heat transport limitations is done using Nano fluid and water as the working fluid with both axially rectangular grooved wick and sintered wick inside copper heat pipe with volume fraction is taken as 1% and their variation is studied with experimental results.

2. MATHEMATICAL MODELING

Assumptions

It is assumed the heat pipe is capillary limited, Heat pipe wick thickness of t_w is much smaller than the vapor core radius, heat flux density is uniform at the evaporator or condenser surface, Thermal conductivity of the liquid-saturated wick is proportional to that of the liquid and there is no slip between particle and continuous phase and Nano fluid is taken as a single-phase fluid. Nanoparticle have an extremely reduced dimensions and thus they can be easily fluidized and as a result nanoparticle can be considered to behave like fluid.

2.1 Geometrical configuration and working

Fig. 1 shows the geometrical configuration and working principle of horizontal copper heat pipe which is under consideration.Basically heat pipe is a vacuum-tight device with a compatible working fluid , wick structure and impermeable walls to prevent any heat loss during the flow of working fluid wick structure. In heat pipe the heat input is given which vaporizes the liquid working fluid inside the wick in the evaporator section. The saturated vapor, carrying the latent heat of vaporization, flows towards the colder condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two-phase flow circulation continue as long as the temperature gradient between the evaporator and condenser is maintained.

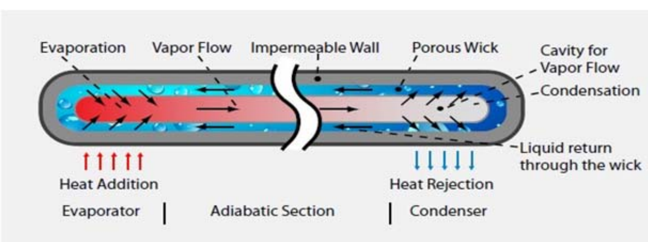


Fig. 1: Working of the Horizontal heat pipe

2.2 Governing equations

For the maintenance of this two phase flow under continuous thermal gradient there are some governing equations under above assumptions are as follows:

The mass and momentum conservation equations for liquid and vapor regions are [6]:

Vapor region

$$\frac{\partial u_v}{\partial x}+\frac{\partial v_v}{\partial r}+\frac{v_v}{r}=0$$

$$\rho_v\left(u_v\frac{\partial u_v}{\partial x}+\frac{\partial u_v}{\partial r}\right)=-\frac{\partial p_v}{\partial x}+\mu_v\left(\frac{\partial^2 u_v}{\partial r^2}+\frac{1}{r}\frac{\partial u_v}{\partial r}\right)$$

$$\frac{\partial p_v}{\partial r}=0 \qquad \text{….(1)}$$

Liquid region

$$\frac{\partial u_l}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}(ru_l)=0$$

$$\frac{\mu_l}{\varepsilon}\left(\frac{\partial^2 u_l}{\partial r^2}+\frac{1}{r}\frac{\partial u_l}{\partial r}\right)-\frac{\mu_l}{K}u_l-\frac{\rho_l F\varepsilon}{K^{1/2}}|u_l|u_l-\frac{\partial p_l}{\partial x}=0 \qquad \text{….(2)}$$

Where K, epsilon and F are porosity,permeabilty and Geometric functions based on wick structure of heat pipe[6].

Pressure diference equations[3]

$$\Delta p_{cap_{max}} \geq \Delta p_l+\Delta p_v+\Delta p_{e_{phase}}+\Delta p_{c_{phase}}+\Delta p_g \qquad \text{….(3)}$$

$$\Delta p_{cap_{max}} \geq \Delta p_l+\Delta p_v \pm \Delta p_g \qquad \text{….(4)}$$

2.3 Analysis

In Fig2. Schematic view of copper heat pipe is given with dimensions given in Table 1. Analysis of operating

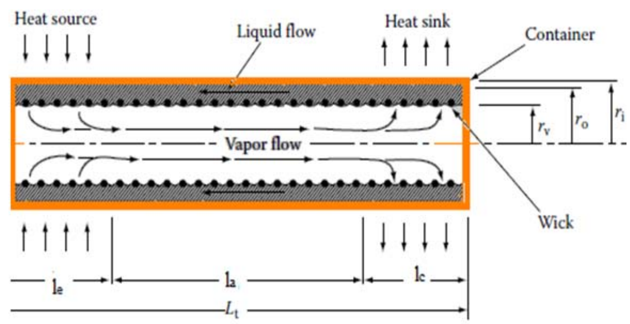


Fig. 2: Schematic representation of the Horizontal heat pipe

Table 1: Heat pipe parmeters

Table 1.Heat pipe parameters

Evaporator length	l_e	0.127	m
Adiabatic length	l_a	0.254	m
Condenser length	l_c	0.127	m
Length of pipe	L_t	0.508	m
Diameter of heat pipe	d_o	0.0127	m
Effective length	l_{eff}	0.381	m
Thickness of Heat pipe	t_p	0.0025	m
Diameter of vapour zone	d_v	0.00914	m
Groove deapth	δ	0.000762	m
Groove width	w	0.000454	m
Wick fin thickness	w_f	0.000302	m
Hydraulic radius of vapour zone	r_{hv}	0.00457	m
Thermal conductivity of Heat pipe	k_{cu}	401	$W.m^{-1}.K^{-1}$
Axial angle	θ	0^0(Horizontal)	degrees

Heat transport limitations depend upon the working fluid, the type of wick structure and the heat pipe operational temperature.

2.3.1 Working fluid

The working fluid must be choose according to chemical

compatibility with the container and wick materials and operating temperature range.Along with this the fluid must have good thermal stability,high wettability,surface tension and other desirable thermo-physical properties include a high liquid thermal conductivity, low liquid viscosity, and low vapor viscosity at specified operational temperature and pressure. For this analysis

(Al_2O_3- water) Nano fluid is used as working fluid with following Properties.-

Table 2:" Thermo-physical properties of Al_2O_3- water Nano Fluid for Operating Temperature range

T_o	ρ_{nf}	σ_{nf}	k_{nf}	μ_{nf}	P_v	ρ_{nfv}	μ_{nfv}
[k]	[kg.m^{-3}]	[N.m^{-1}]	[W.m^{-1}.K^{-1}]	[N.s.m^{-2}]	[pa]	[[kg.m^{-3}]	[N.s.m^{-2}]
293	1029	0.06448	0.6164	0.01026	2338	41.02	0.0000998
303	1027	0.06376	0.6341	0.00816	4246	41.03	0.000103
313	1023	0.06292	0.6496	0.00669	7383	41.05	0.000106
323	1019	0.06197	0.6629	0.00561	12350	41.08	0.000110
333	1014	0.06092	0.6739	0.00478	19941	41.13	0.000114
343	1009	0.05976	0.6828	0.00414	3118	41.20	0.000116

2.3.2 Wick structure

The forces required to pump liquid from the condenser to the evaporator keeping liquid evenly distributed in the wick is produced by type of wick structures.In this paper axially rectangular grooved wick and sintered wick is used

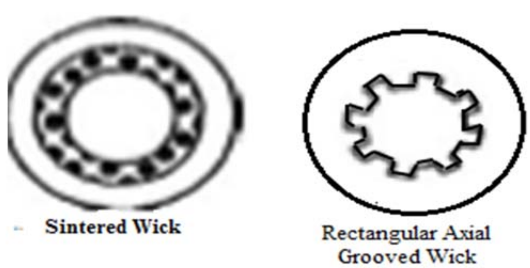


Fig.3. Types of wick structures

2.4 Heat Transport Limits [3]

2.4.1 Boiling limit

Boiling limit occurs when the heat flux density is great enough to cause the saturation vapour pressure at the interface between the wick and the wall to exceed the liquid pressure at the same point.This causes, vapor bubbles formation in the liquid stream.and bubbles form hot spots and restrict liquid circulation, leading

to wick dryout of heat pipe Boiling limit equation given by Chi is-

$$Q_{bm} = \frac{4 \cdot \pi \cdot l_{eff} \cdot k_e \cdot T_i \cdot \sigma_1}{\lambda_1 \cdot \rho_2 \cdot \ln\left[\frac{r_i}{r_v}\right]} \cdot \left[\frac{1}{r_n} - \frac{1}{r_c}\right] \quad ....(5)$$

The boiling limit depends upon the wick structure and in this analysis there are two types of wick used i.e. axially grooved rectangular wick and sintered wick[Fig3],hence equations of effective thermal conductivity for former is:

$$K_{egw} = \frac{w \cdot k_1 \cdot (0.185 \cdot w_f \cdot k_{cu} + \delta \cdot k_1) + w_f \cdot k_1 \cdot k_{cu} \cdot \delta}{(w + w_f) \cdot (0.185 \cdot w_f \cdot k_{cu} + \delta \cdot k_1)} \quad ....(6)$$

And for latter is:

$$k_{esw} = k_{cu} \cdot \left[\frac{2 + \frac{k_1}{k_{cu}} - 2 \cdot 0.48 \cdot \frac{k_1}{k_{cu}}}{2 + \frac{k_1}{k_{cu}} + 0.48 \cdot \left(1 - \frac{k_1}{k_{cu}}\right)}\right] \quad ...(7)$$

Hence amount of heat input should be less than this limit.

2.4.2 Capillary limit

The capillary limit governs heat pipe operation by developing capillary pressure difference across the liquid-vapour interfaces in the evaporator and condenser and when the driving capillary pressure is insufficient to provide adequate liquid flow from the condenser to the evaporator, dryout of the evaporator wick will occur. Chi has derived the equations for determining thecapillary or wick heat transport limit-

$$Q_{cm} = \sigma_1 \cdot \rho_1 \cdot \frac{\lambda_1}{\mu_1} \cdot K_e \cdot \frac{A_v}{l_{eff}} \cdot \left[\frac{2}{r_c} + \rho_1 \cdot g \cdot L_t \cdot \frac{\cos(\theta)}{\sigma_1}\right] \quad ....(8)$$

2.4.3 Sonic Limit

Sonic limit governs occurrence of choked flow in the vapour passage which can be possible due to very high vapor velocities at low vapour densities. Equation for sonic limit is given by Levy.-

$$Q_{sm} = 0.474 \cdot A_v \cdot \lambda_1 \cdot (\rho_2 \cdot P_v)^{0.5} \quad ....(9)$$

2.4.4 Entrainment Limit

Entrainment limit is a result of shear forces devolped over saturated wick during the interactions between the vapor stream and the liquid stream in counter flow direction which results in insufficient liquid flow to evaporator wick causing wick dry out rapidly. Chi also developed its equation:-

$$Q_{em} = A_v \cdot \lambda_1 \cdot \left[\frac{\sigma_1 \cdot \rho_2}{2 \cdot r_{hs}}\right]^{(1/2)} \quad ....(10)$$

2.4.5 Vapor Limit

The viscous limit occurs at low operating temperatures, where the saturation vapour pressure may become equal to the pressure drop required to drive the vapor flow in the heat pipe which results in insufficient pressure difference to drive the liquid.

$$Q_{vm} = \frac{\pi \cdot r_v^4 \cdot \lambda_1 \cdot \rho_2 \cdot P_v}{12 \cdot \mu_2 \cdot L_{eff}} \quad ….(11)$$

2.5 Heat Transfer Coefficient

Heat transfer coefficient inside the heat pipe is analysed by internal resistance approach thereby by improving the thermal performance of heat pipe and solving the high heat flux dissipation problem using nano fluid.

$$U_{hp} = \frac{1}{R_{pe} + R_{we} + R_v + R_{wc} + R_{pc}} \quad …(12)$$

2.5.1 Equations [4]

Resistance of heat pipe at evaporator

$$R_{pe} = r_0 \cdot \frac{t_p}{2 \cdot l_e \cdot k_{cu}} \quad ….(13)$$

Resistance of wick at evaporator

$$R_{we} = r_0^{\,2} \cdot \frac{t_w}{2 \cdot l_e \cdot r_i \cdot k_e} \quad ….(14)$$

Resistance of vapor

$$R_v = \pi \cdot r_0^{\,2} \cdot F_2 \cdot \left[\frac{l_e}{6} + l_a + \frac{l_c}{6}\right] \cdot \frac{T_0}{\rho_2 \cdot \lambda_1 \cdot J} \quad …(15)$$

F_2=vapor friction factor, J=mechanical equivalent

Resistance of heat pipe at condenser

$$R_{pc} = r_0 \cdot \frac{t_p}{2 \cdot l_c \cdot k_{cu}} \quad ….(16)$$

Resistance of wick at condenser

$$R_{wc} = r_0^{\,2} \cdot \frac{t_w}{2 \cdot l_c \cdot r_i \cdot k_e} \quad ….(17)$$

t_w = wick thickness

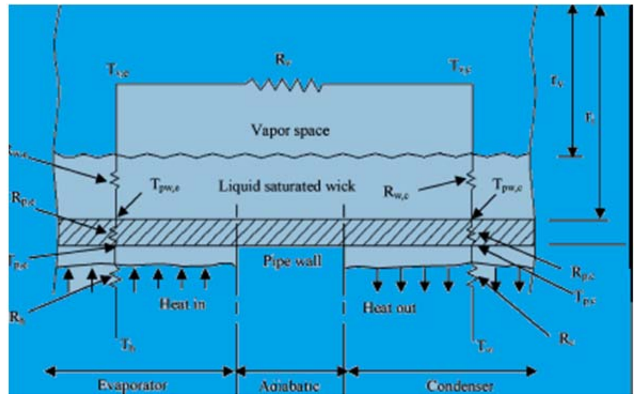


Fig. 4: Internal Resistance approach and parameters

2.6 Nano Fluid

In our analysis (Al_2O_3- water) nano fluid is used as working fluid with volume fraction φ=1% and its comparison is done with the base fluid water

2.6.1 Equations [1]

Thermal conductivity of nano fluid

$$k_{nf} = \left[\frac{k_p + 2 \cdot k_{bf} + \left(2 \cdot (k_p - k_{bf}) \cdot (1+\beta)^3\right) \cdot \phi}{k_p + 2 \cdot k_{bf} - \left(2 \cdot (k_p - k_{bf}) \cdot (1+\beta)^3\right) \cdot \phi}\right] \cdot k_{bf} \quad ….(18)$$

Density of nano fluid

$$\rho_{nf} = \phi \cdot \rho_p + (1 - \phi) \cdot \rho_{bf} \quad ….(19)$$

Viscosity of nano fluid

$$\mu_{nf} = \mu_{bf} \cdot (1 + 2.5 \cdot \phi) \quad ….(20)$$

So above equations are used for enhancement of heat transfer in heat pipe using nano fluid instead of base fluid

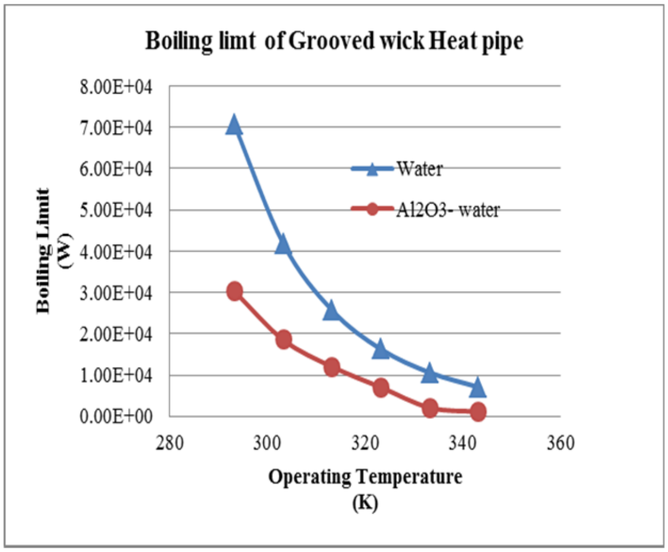
3. RESULTS AND DISCUSSION

3.1 Heat Transport Limitations

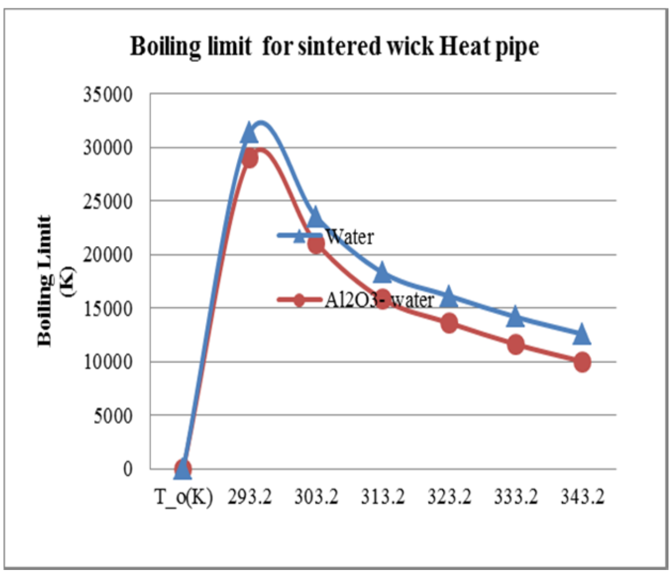
The capillary limits and boiling limits are most important for heat pipe design and operation so our results is more focussed toward these two limits as these two limits vary with wick structures and are significant.

3.1.1 Boiling limit

In graph1 and graph2 boiling limit of the heat pipe with grooved wick and sintered wick is shown respectively for both nano fluid and water. In case of rectangular axial grooved wick there is lot of difference in the limit for two fluid whereas in graph2 there is not much difference in limits for both fluids.



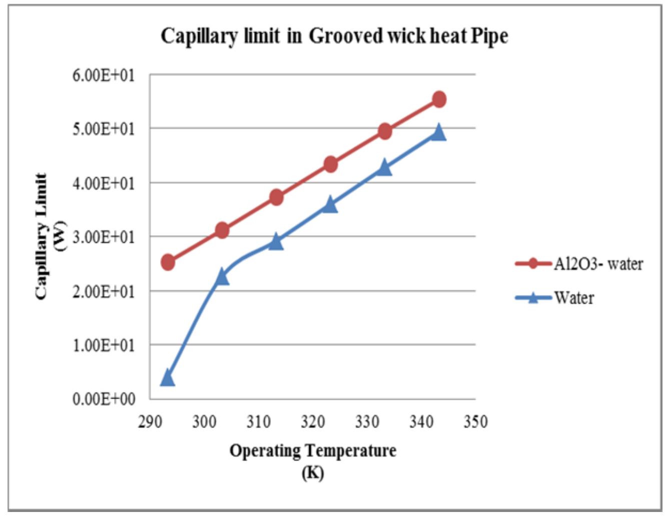
Graph 1: Boiling limit of grooved wick Heat pipe



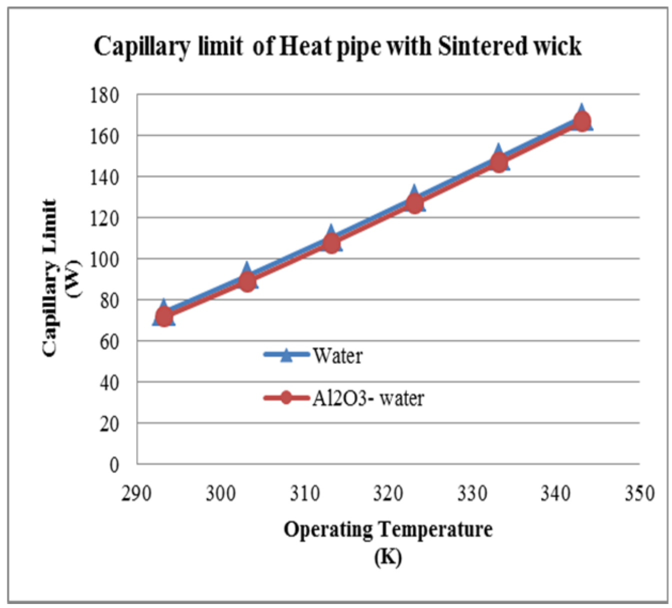
Graph 2: Boiling limit for sintered wick Heat pipe

3.1.2 Capillary Limit

In graph3 there is a high difference in capillary limits for grooved wck pipe for both the fluids and value of capillary limt in graph 4 for sintered is much higher and relate closely for both fluids.



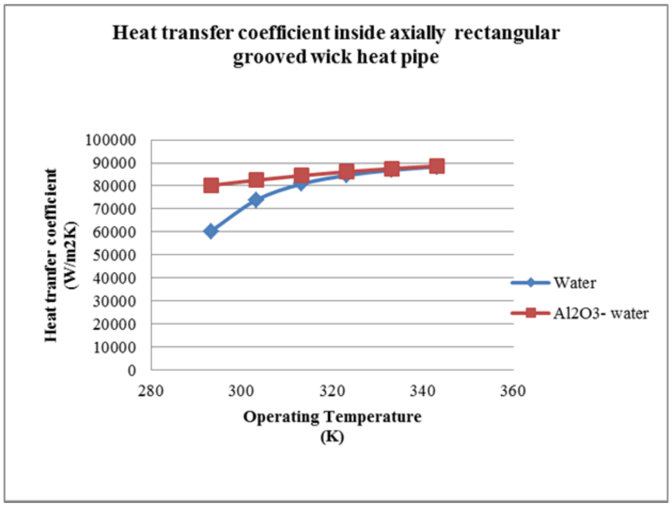
Graph 3: Capillary limit in grooved wick heat pipe



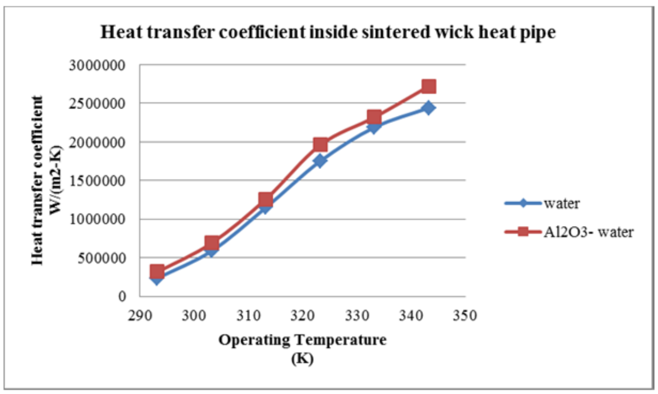
Graph 4: Capillary limit of sintered wick heat pipe

3.2 Heat Transfer coefficient

In graph 5 and graph 6 the variation of heat transfer coefficient for both the fluid and for both the wick structure is shown and it is obseved that heat tansfer coefficient increases up to 7.33% in rectangular axial grooved wick by using (Al_2O_3- water) Nano fluid and in case of Sintered it increases up to 10.91%.



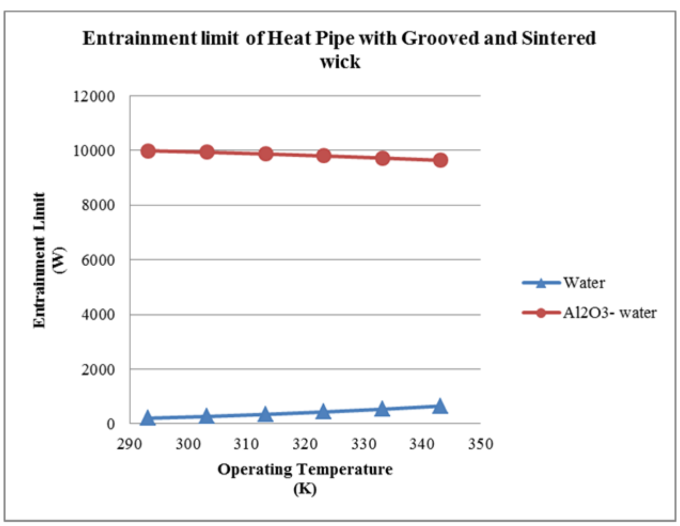
Graph 5: Heat transfer coefficient inside axial rectangular grooved wick heat pipe



Graph 6: Heat transfer coefficient inside sintered wick heat pipe

3.3 Entrainment limit

As discussed in 3.1 section the other limits are insignificant as shown in graph 7.Here Entrainment limit



Graph 7: Entrainment limit of Heat pipe

for nano fluid is so high than water that there can be no comparison between the two limits and it is also not dependent on types of wick structures, like wise similar is the case with sonic limit and vapour limit.

4. CONCUSION

The heat transfer coefficient and heat transport limitations is numerically investigated using Al_2O_3-water nanofluid (φ =1%) inside a copper heat pipe. Following conclusions have been obtained:

In case of Heat transfer coefficient inside the heat pipe there is a increase of 7.33% with axially rectangular grooved wick as compared to 10.19% by using sintered wick structures when compared to base fluid. This is mainly due to increased conductivity of nanofluid and due to increased effective conductivity of sintered wick heat pipe as compared grooved wick heat pipe.

In case of Heat Transport limitations the values of capillary and boiling limits is higher in sintered wick heat pipe which basically governs the amount of power or heat input given to heat pipe and plays a crucial role in increased themal performance of heat pipe.

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