Heat Transfer Enhancement in A Grooved Heat Pipe Using Nanofluids

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ABSTRACT

Aluminum oxide nanofluids as a working fluid was applied for the heat transfer enhancement of a rectangular groove heat pipe and compared with a heat pipe that only used distillated water. The heat pipes had the same dimensions and were made of aluminum 6061. The dimensions were 135.6mm x17mm x 10.3mm respectively; the rectangular grooves consisted of 0.794mm of width and 1.587mm depth. The two heat pipes were tested individually and subjected to the same boundary conditions. One side of the heat pipe was in contact with a hot plate set at a constant temperature, and the other side was exposed to ambient conditions. One heat pipe was tested with distillated water and the other one with distilled water and nanofluids in a fraction of 1:10 in volume. According to the experiments results the performance of the heat pipe with the nanofluid as a working fluid was the most efficient. It was found that the heat transfer increased by 14.14% compared with the heat pipe that used distillated water only. It can be concluded that the heat transfer enhancement was due to the presence of the nanofluids that increased the effective thermal conductivity of the working fluid.

Keywords: heat pipe, nanofluid, heat transfer enhancement, effective thermal conductivity.

RESUMEN

Nanofluidos de óxido de aluminio se aplicó para la mejorar la transferencia de calor de un tubo de calor con ranura rectangular. La data experimental se comparó con un tubo de calor que sólo utilizaba agua destilada. En ambos casos los tubos de calor tenían las mismas dimensiones y estaban hechas de aluminio 6061. Las dimensiones fueron 135.6mm x17mmx 10.3 mm, respectivamente. Las ranuras fueron rectangulares y consistieron de 0.794mm de anchura y una profundidad de 1.587mm. Los dos tubos de calor fueron probados individualmente y sometidos a las mismas condiciones de contorno. Un extremo del tubo de calor se puso en contacto con una placa caliente a una temperatura constante, y el otro lado fue expuesto a las condiciones ambientales. Un tubo de calor se puso a prueba con agua destilada y el otro con agua destilada y nanofluidos en una fracción de 1:10 en volumen. De acuerdo con los resultados experimentales el rendimiento de la tubería de calor nanofluidos como un fluido de trabajo fue el más eficiente. Se encontró que la transferencia de calor se incrementó en 14,14 % en comparación con el tubo de calor que utiliza solamente agua destilada. Se puede concluir que la mejora de la transferencia de calor fue debido a la presencia de los nanofluidos; los nanofluidos incrementaron la conductividad térmica efectiva del fluido de trabajo.

Palabras claves: tubo de calor, nanofluido, transferencia de calor, conductividad térmica efectiva.

1. INTRODUCTION

Heat pipes are able to transfer energy from a hot to a colder source faster than by pure conduction heat transfer (Queheillalt et al, 2008). Heat pipes have been applied to several applications for industry, electronic cooling, aerospace, etc. Heat pipe apart of being a passive device has the advantage to work in vertical direction against the acceleration of gravity. The capability to remove heat from an electronic component is a key challenge in thermal management when maintaining a component at acceptable operating temperatures (Gillot et al., 2004 and Peter J. de Bock et al., 2008) . Fluids are often applied to carry heat from a hot device. The development of high thermal conductivity fluids has been applied; it has been found that metallic liquids thermal conductivity is much greater than of nonmetallic liquids (Peterson G.P. and Li C.H., 2006). In order to take advantage of this type of technology several heat pipes have been designed in order to be embedded into heat sinks to facilitate heat transfer (Peter J. de Bock et al., 2008) . Previous experimental investigations have revealed that nanofluids present higher thermal conductivity than conventional fluids. Ma et al. 2006, shown that nanofluids increased the heat transport capability of an oscillating heat pipe. Using diamond nanofluids were able to reduce the temperature difference between the condenser and evaporator by approximately 41 percent. Wang et al., 2005 reported an increment of the heat transfer coefficient of the evaporator and the critical heat flux of a horizontal micro-grooved heat pipe when substituted CuO nanofluids for water. Tsai et al., 2004, compared the effect of nanofluids on the thermal efficiency of a heat pipe. It was shown that the thermal resistance with gold nanoparticles was lower than pure distilled water as a working fluid . Wei et al., 2005, measured the thermal effect of silver nanoparticles in heat pipes; it was proved that nanofluids as a working fluid increased the thermal efficiency of the heat pipes. Heat pipes elements are considered to have higher thermal conductivity compared to those of a homogenous piece (El-Nasr A. A., El-Haggar S. M., 1996). In this work a rectangular groove heat pipe with aluminum oxide nanofluid as working fluid was investigated and compared with distilled water.

2. EXPERIMENTAL SETUP

In order to conduct the experiment a vacuum process is needed to be made for each heat pipe. Figure 1 shows the schematic of the vacuum and working filling process. The filling/ vacuum system is connected to the heat pipe the fitting valve and the hose valve are open until the vacuum process is completely made at working temperature by means of adding heat to the heat pipe with the heat source. The heat pipe is to be filled with the corresponding amount of fluid by means of a needle after the vacuum process has been done.

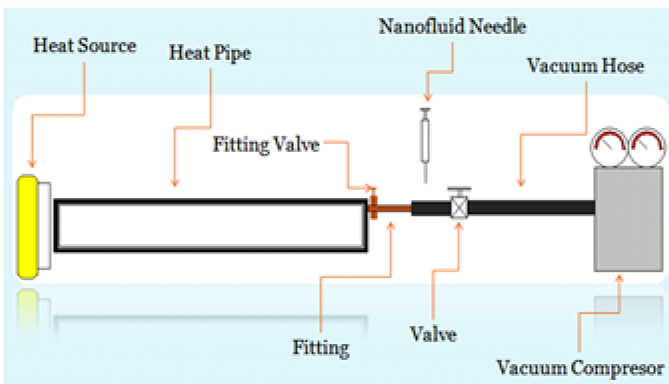


Figure 1: Working Fluid Filling/ Vacuum Setup

When the filling/ vacuum process has been done the setup for the temperatures and heat transfer is then assembled as show in Fig. 2. This setup consists on a stand for the heat source; five thermocouples type K already calibrated were connected to the DAQ, the computer which records all the data from the experiment on a LabVIEW program and the stand which will be supporting the heat pipe in place for the experiment tests.

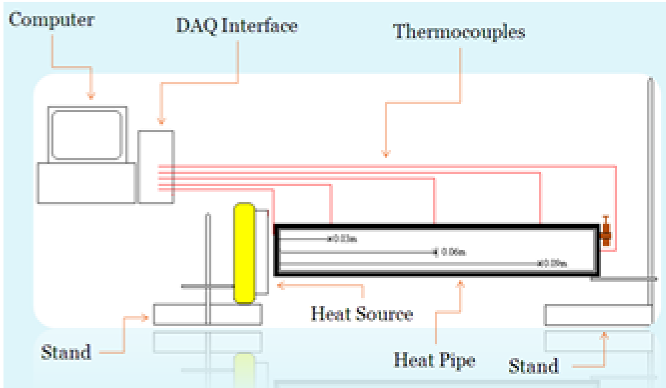


Figure 2: Temperatures Measurements Setup

3. THEORETICAL MODEL

When it comes to the thermal analysis of the heat pipe and justifying why it is so efficient when it comecomes to transfer heat, basically is because of the low thermal resistance due to the convective flow. This low thermal resistance is due to small length of heat transfer through solid walls as shown in Fig. 3. Therefore the entire problem can be reduced into a simple heat transfer problem.

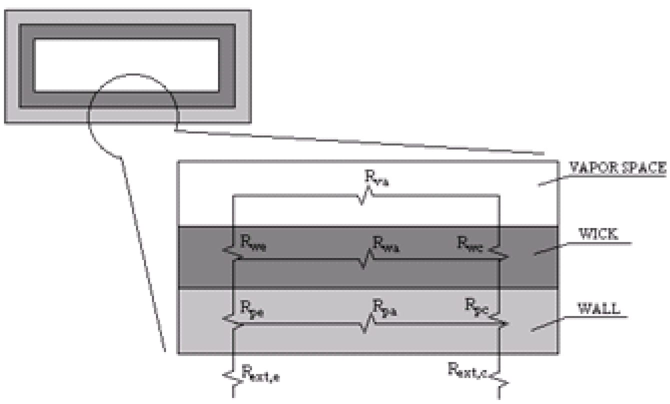


Figure 3: Heat Pipe Thermal Resistances Representation

Due to length properties almost zero energy is transported from the hot side to the cold side by means of the pipe Rw and the capillary structure Rc due to the high heat resistance as shown in Table 1. Therefore it is possible to neglect the resistance of the flow Rv, because it is very low (Peterson G.P., 1994)

Table 1: Comparative Values for Heat Pipes Resistances (Peterson G.P., 1994)

Resistance	ºC/W
$R_{p,e}$ and $R_{p,c}$	10^{-1}
$R_{w,e}$ and $R_{w,c}$	10^{+1}
$R_{i,e}$ and $R_{i,c}$	10^{-5}
$R_{v,a}$	10^{-8}
$R_{w,a}$	10^{+2}
$R_{p,a}$	10^{+4}

Therefore the entire thermal resistance of the heat pipe can be described as:

$$R_{HP}=R_{w,e}+R_{p,e}+R_{w,c}+R_{p,c} \quad (1)$$

According to Maxwell first fundamental equation for the prediction of effective thermal conductivity of solid particles and fluid mixtures, by assuming that the nanoparticles are of a spherical shape and that the volume fraction (ϕ_s)is relatively low, the calculation for the effective thermal conductivity, k_{eff}, for the nanofluid can be obtained from (Peterson G.P. and Li C.H., 2006):

$$\frac{k_{eff}}{k_l}=\frac{k_s+2k_l+2(k_s-k_l)\phi_s}{k_s+2k_l-(k_s-k_l)\phi_s} \quad (2)$$

Also for the effective thermal conductivity for liquid saturated wick structures for rectangular grooves it is calculated as follows (Peterson G.P., 1994):

$$k_{eff,w}=\frac{(w_f k_l k_w \delta)+wk_l(0.185w_f k_w+\delta k_l)}{(w+w_f)(0.185w_f k_w+\delta k_l)} \quad (3)$$

The heat transfer from the two heat pipes and the solid block were evaluated between the thermocouple located at 30mm and 90mm. By obtaining the temperature difference of the two thermocouples and calculating the thermal resistance (R) from the heat pipes and the solid block the heat transfer then can be obtained by the following formula:

$$R=\Delta T/Q \quad (4)$$

where ΔT is the temperature difference between the thermocouples and R is the thermal resistance of the thermal system in study. Between all the limitations that can be encountered in a heat pipe like the melting temperature, viscosity limit, speed of sound limit, interaction limit, boiling limit and critical temperature, the capillary limit is the most commonly encountered limitation of low-temperature heat pipes. Figure 4 shows the dimensions of the current groove for the heat pipe in study.

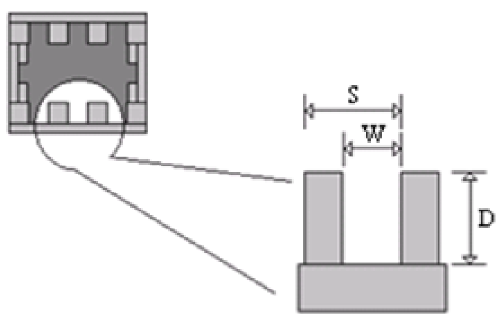


Figure 4: Grooves Dimensions Representation

The surface tension, density of the liquid and vapor water at 25 degrees Celsius are: σ = 0.061 N/m, ρ_l = 958.3 kg/m^3, ρ_v = 0.597 kg/m^3 and assuming perfect wettability (θ = 0 degrees) [9], the capillary pressure for the rectangular groove of the heat pipe is determined by:

$$P_{cap}=\frac{\sigma_{lv}\left[(2D+W)\cos\theta-W\right]}{DW} \quad (5)$$

By the application of Eq. (5) for the heat pipes in study the capillary pressure resulted to be 192N. Also the height of the liquid column form the capillary effect can be obtained from Eq. (6) resulting to be 1.56mm (Wei et al., 2005):

$$H=\frac{\sigma_{lv}\left[(2D+W)\cos\theta-W\right]}{\rho_l gDW} \quad (6)$$

To determine the amount of working fluid for the heat pipe to work effectively, it was necessary to calculate the values from basic thermodynamics analysis. Assuming the fluid properties at 25ºC, the specific volumes for the liquid and vapor phase are: $\upsilon_f = 0.001003\ m^3/kg$ and $\upsilon_g = 42.34\ m^3/kg$. As seen in Fig. 5 the volumes for the vapor and liquid are represented inside the system; for the analysis it was assumed that the liquid cover 50% of the groove height and all the free space was occupied by water vapor.

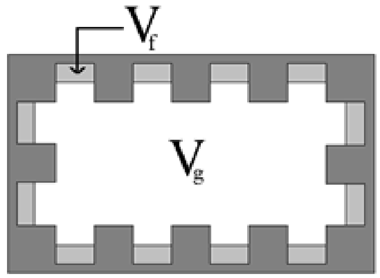


Figure 5: Grooves Dimensions Representation

Thus, after calculating the volume of the liquid and vapor phases, the total mass of the working fluid is calculated as follows:

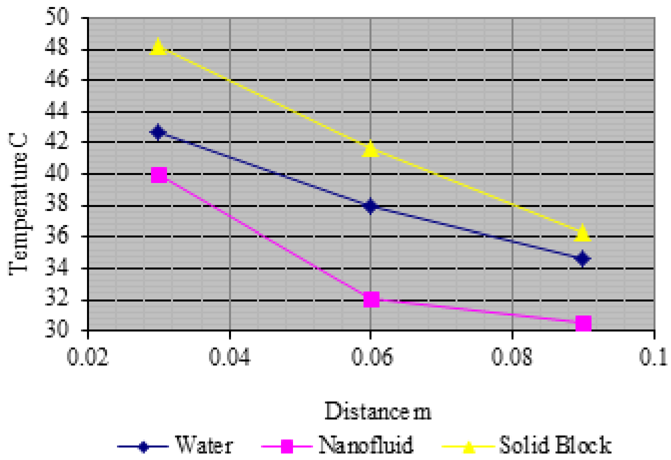
$$m_{total} = \frac{\forall_f}{\upsilon_f} + \frac{\forall_g}{\upsilon_g} \quad (7)$$

The final mass for the system is 20% more than the total mass calculated from the thermodynamic formula, Eq. (7), due to the losses in the filling system. When it comes to the nanofluid the amount needed will be 10% more than from the distillated water.

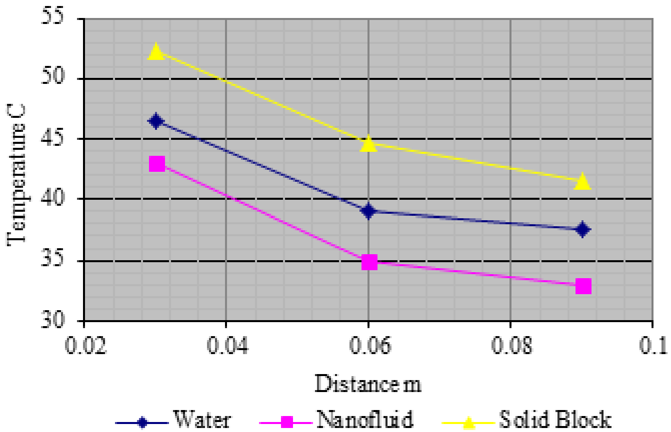
4. RESULTS AND DICUSSIONS

Figure 6 shows the wall temperature distribution at different locations along the axial length of the heat pipe. The temperature distribution in Fig. 6-(a) corresponds to an input temperature of 205°C applied on the left side of the heat pipe (see Fig. 2). Similarly in Fig 6-(b) is depicted the temperature distribution for a fixed temperature input of 220°C. A quite similar temperature distribution response is observed in both cases; also it can be observed that the lowest temperature distribution corresponded to the heat pipe with nanofluids. The lowest temperature drop along the axial direction was 8 °C and corresponded to the input temperature of 205 °C. Figure 7 (a) shows that wall temperature distribution for the three thermocouples placed at 30mm, 60mm and 90mm of the heat pipe containing distillated water were 42.7℃, 38.0℃ and 34.6℃, respectively. After mixing 10 percent of nanofluid with distilled water heat pipe, it can be seen that the temperature distribution decrease in the wall temperature of heat pipe in the order of 40.0℃, 32.1℃ and 30.5℃, and for the solid block the temperatures obtained were of 48.3℃, 41.6℃ and 37.3℃, respectively. The both situations in which the experiments were tested showed the same behavior one form another differenced only by the increment in temperature from the thermocouples due to the increment in temperature from the heat source.

The total heat pipe resistance (HPR) could also be obtained from Eq. (1) for the both of the heat pipes experiments. To be able to determine this values from Eq. (2) the effective thermal conductivity for the nanofluid must be calculated, resulting 0.768 W/m•K. The thermal conductivity of the wick structure with the nanofluid as working liquid form Eq. (3) came to be 85.35 W/m•K and 85.27 W/m•K for the distillated water. With the results already obtained we can then obtain a total heat pipe resistance of 0.245 K/W for the heat pipe with distillated water and 0.245 K/W also for the heat pipe with nanofluid. Therefore form the Eq. (4) we can then obtain the heat transfer along the heat pipe showing an increment of the heat transfer by 14.14% between the distillated water and the nanofluids heat pipes and 60.79% between the nanofluids heat pipe and the solid block for the 215℃ heat input from the heat source test. As seen on Fig. 7 the temperature vs. time shows that the steady state conditions for the heat pipes is reached faster than the solid block. It can be stated that heat pipes are more efficient than solid materials; not only in removing high heat faster than a solid block, but also in reaching its steady temperature faster than the solid material.

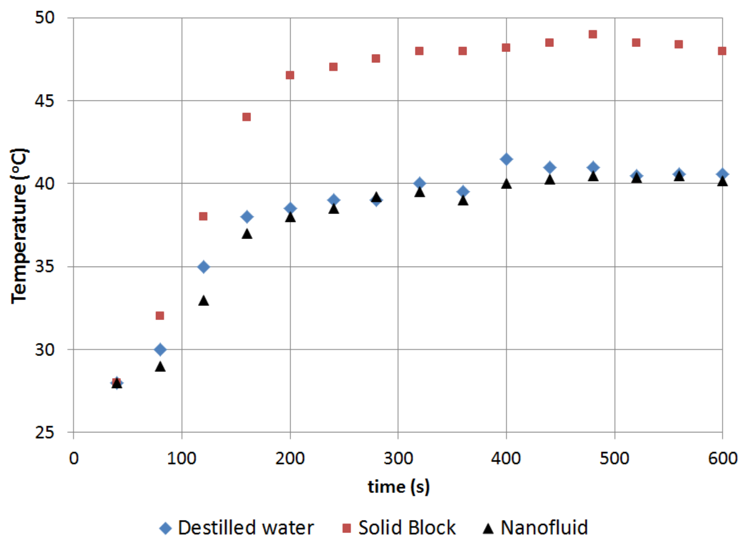


(a)

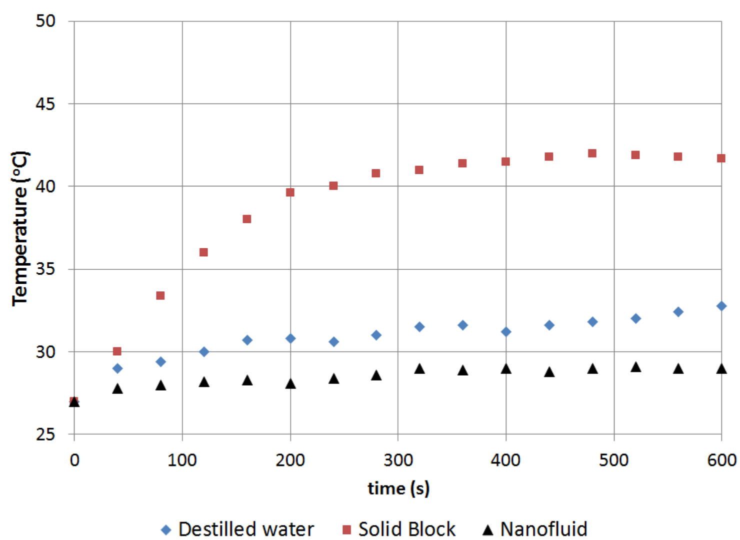


(b)

Figure 6: Boundary conditions (a) 205°C Hot Plate Temperature vs. Axial Distance, (b) 220°C Hot Plate Temperature vs. Axial Distance



(a)



(b)

Figure 7: (a) Temperature vs. Time for the thermocouple at 0.03m, (b) Temperature vs. Time for the thermocouple at 0.09m

5. Conclusions

In the present study, the thermal performance of a rectangular grooved heat pipe using aluminum oxide-nanofluid with diluted 45nm nanoparticles as the working fluid was compared with a rectangular grooved heat pipe without nanoparticles (distillated water). The rectangular grooved heat pipes and an aluminum solid block with the same outer dimensions were also experimentally tested. The experimental data reveals that the thermal performance of the heat pipe with nanofluid considerably increased. It was assumed that the major reason for increasing the thermal performance of heat pipe was the increase of the effective thermal conductivity of the working fluid in the liquid phase. According to the calculated heat transfer rate it was found that the nanofluid heat pipe clearly showed and increment of 14.14% compared with the heat pipe with distillated water, and 60.79% compared with the solid block. Therefore, it was shown that the thermal performance of heat pipe was enhanced. As a result, the higher thermal performance of the nanofluid than distilled water has proved its potential thermal benefits of using nanofluids for new generation of grooved heat pipe.

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