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Experimental Study on the Effect of Water as a Working Fluid in Aluminium Heat Pipes

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Abstract

Thermal management of machines and electronic devices is a matter of high importance. Cooling of electronics becomes much more sensitive in applications related to space because of the difficult constraints and environment. The weight and size are very important parameters as well as the efficiency of the cooling method and heat pipes are considered a very suitable option because of its passive operation and light weight. Different working fluids can be used in a heat pipe but the compatibility of the casing material with the working fluid is a very important parameter. Water aluminum heat pipes are not a common option because they react at temperatures starting from 294 K. In this research the effect of water in the degradation of the performance of aluminum heat pipes is studied. A suitable operation range for the heat load is considered. It is found that at higher loads, the performance of the heat pipe decreased but with the addition of nano particles the performance was compensated by a large measure.

Keywords: *Aluminum water heat pipe; Grooved Heat pipe; Hydrogen formation in heat pipe; Nanoparticles*

1. Introduction

Heat pipes are considered one of the best technologies to cool electronic devices. It is considered an efficient device with high thermal conductivity because the working fluid inside the pipe changes phases leading to the transfer of a substantial amount of heat. Heat pipes are considered a passive technology because it lacks moving parts or mechanisms during its operation. Heat pipes consists of a casing material, a working fluid, and a return mechanism. The casing material is usually made of metal and the working fluid depends on several parameters such as the operating temperature of the heat pipe which is the phase change temperature of the fluid from liquid to vapor and vice versa. There are other considered parameters including the wettability, heat transfer capabilities and the compatibility of the working fluid with the casing materials [1]. The compatibility parameter is important to ensure the nonreactivity of the working fluid with the casing and consequent degradation of the performance. When discussing the casing material, metals are highly preferred such as aluminum, copper ad stainless steel, owing to their high conductivity and mechanical strength. Aluminum is considered a plausible option for many applications because of its lightweight [1]

It became known that the water working fluid and aluminum casing heat pipes are non-compatible due to the propensity of the following possible reactions [2].

$$2Al + 6H_2O = 2Al(OH)_3 + 3H_2 \quad (1)$$

$$2Al + 4H_2O = 2AlO(OH) + 3H_2 \quad (2)$$

$$2Al + 3H_2O = Al_2O_3 + 3H_2 \quad (3)$$

These reactions generate hydrogen gas that degrades and alters the composition of the working fluid that compromises the performance of the heat pipe. Godart et al. reported that the onset temperatures of these reactions (1 to 3) is 294 [3]. Despite the reactivity drawback using water-aluminum heat pipe, this combination poses other advantages. Chiefly is the light weight of the aluminum and the ease of using water for space application environment specifically in the temperature range 303-550 K [4] [5]. To demonstrate this added benefits, several attempts were made by Xie et al [6] the authors coated the inner surface of the walls with chrome and mitigated performance loss after extended operation. Chang [7]. developed an aluminum water heat pipe with a coating formed by the hydration layer $Al(OH)_3$ at the inner casing surface that follows the reaction in Eq. **Error! Reference source not found.**. Researchers have been continuously developing methods to enhance the performance of heat pipes.

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Amongst these methods is the addition of nano particles that 05Specifically, the increase of the thermal conductivity and improve the nucleation of the working fluid to accelerate the evaporation process. Mashaie and Shahryari experimentally used different nano particles in the working fluid and reported significant increase in the heat transfer coefficient. It was attributed to the reduction in thermal resistance of the saturated porous media [8] . Kim and Bang [9] also reported an enhancement in the graphene oxide (GO-H_2O) nano fluid mixture heat pipe. The GO-H_2O heat pipe reported a 25% decrease in thermal resistance in the evaporator side. Furthermore, they showed that the capillary limit in GO-H_2O heat pipe was higher. A study done by Kya and Seok [10] showed the feasibility of doubling the thermal performance when using water based Al_2O_3 nanofluid at concentrations below 0.1%.

In this work, we intend to experimentally study the effect of water aluminum reaction on the performance of the heat pipe. The author recently reported numerical simulation on a grooved heat pipe [11], and earlier extensive parametric study on the porosity, evaporator and condenser length and pipe diameter as well as the heating load [12] [13]. This work focuses on the experimental activities of this research which involves the fabrication and testing the heat pipe at different heat loads. The goal is to fabricate and assess the performance of the heat pipe and to seek its maximum allowable heat load and the performance.

2. Methodology

A heat pipe design was chosen for the purpose of conducting a sensitive study. A grooved heat pipe with Omega cross-sectional shape is selected following the recommendation of Chen et al because it is one of the best options for space applications [14]. **Error! Reference source not found.** shows the dimensions of the heat pipe. The length of the heat pipe is 300 mm and the corresponding lengths of the evaporator, condenser and the adiabatic sections are 72 mm, 93 mm and 135 mm respectively. The outer diameter of the heat pipe is 15 mm, the inner diameter is 10 mm, and the diameter of the grooves is 1.2 mm

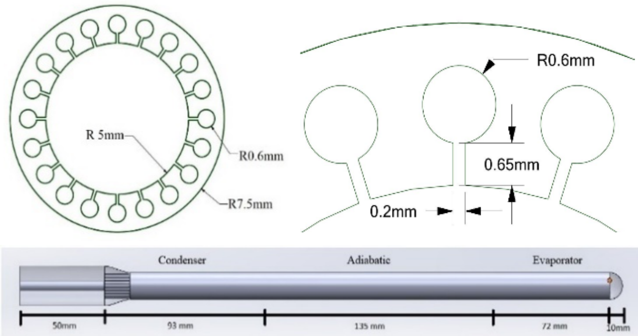

Fig. 1: Dimension of the heat pipe with internal cross section

as illustrated in **Error! Reference source not found.**.

The heat pipe was fabricated using metal 3D printer. The material used was alumina silicon powder. The used printed is referred to as (EOS M290). A German technology at KU Additive manufacturing Lab. The condenser end was additionally thickened for machining and threading to Facilitate working fluid handling and filling.

Fig 2 shows the setup and all the components used for the 30 cm long and 2cm diameter heat pipe. The heat pipe (1) is rigidly seated on two acrylic supports material prepared using NC machine using laser cutting technology. The heat source (2) is a type of silicon heating thin, flat, and flexible cord which is regulated by the power supply (4) and is placed on the evaporator. It covers nearly 90% of the evaporator side. Ten thermocouples (3) are connected to the heat pipe, of which four are mounted on the evaporator section, two on the adiabatic section and four on the condenser section. These thermocouples are connected to the data acquisition card (5) which samples the data at the stipulated sampling rate (1-10Hz). The data is processed with the LabVIEW software (6). The nano particles used in this experiment is alumina oxide, Sigma-Aldrich/Canada with an average size of 69 nm.

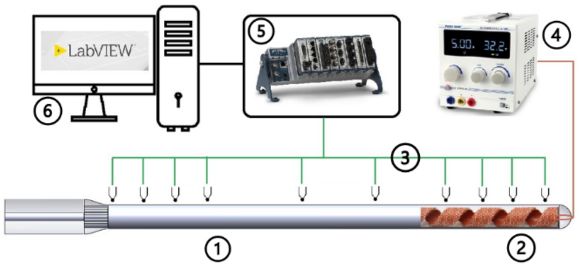

Fig 2: Experimental setup for the heat pipe, 1: Heat pipe unit, 2: Heat source, 3: Thermocouples, 4: Power source, 5: DAQ system, 6: Computer for data analysis

Three different weight percentages were considered based on a study by Huminic [15]. Accordingly, percentages of 0.25%, 0.5% and 1% wt were used. The Alumina nano particle was mixed with the stipulated amount of water and filled inside the heat pipe using medical syringe as illustrated in Fig. 3. A 35% filling ratio was used for this experiment and kept constant while varying the heat load. After filling the heat pipe with the correct filling ratio, its end is tightly closed with a threaded cap. To ensure the closed system be completely pure and only filled with water liquid and vapor, the heat pipe is seated horizontally and heated rapidly to evaporate the water and consequently pushes out the air and any other gases, and after a few seconds the heat pipe is closed off.

Fig. 3: Filling the heat pipe with the syringe

Following the end cap closing, the heat pipe is insulated at the evaporator and the adiabatic sections as can be seen in **Error! Reference source not found.**. The condenser side was left open to the ambient as the atmosphere is considered the heat sink.

Fig. 4: Insulation applied on the heat pipe

The heat pipe was heated at three different heat loads, 5, 10 and 15 watts. These heat loads conditions were taken from a simulated scenarios for a small satellite orbiting in the low earth orbit at 420 km and subjected to direct solar radiation. These conditions along other orbital data is provided in a commonly used Cube-sat wizard application with an interface window shown in Fig. 5 and illustration depicted in **Error! Reference source not found.**.

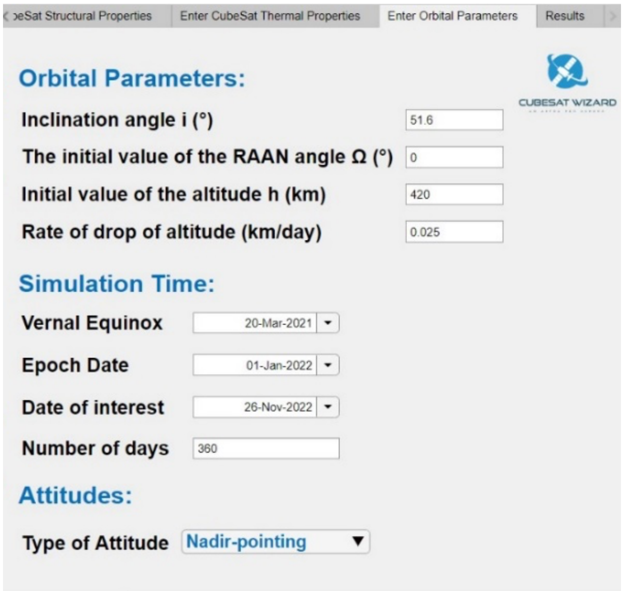

Fig. 5: Orbital parameters input for CubeSat wizard

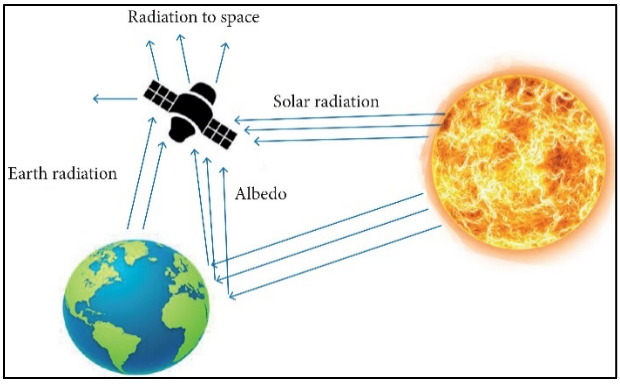

Fig. 6: Simulated heat loads applied to the orbiting satellite in space

Following the interface with CubeSat wizard using the parameters above (**Error! Reference source not found.** the average heat loads is evaluated per Fig. 7. It shows the different heat sources affecting a satellite in orbit. The solar radiation is the direct heat radiation coming from the sun. Albedo is the solar radiation reflected from the surface of Earth and the last source is the infrared radiation released from the earth when heated by the sun.

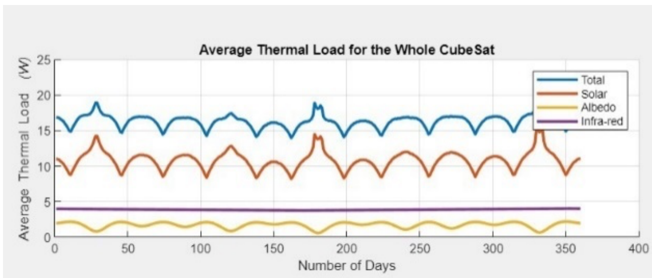

Fig. 7: Average heat loads evaluated via CubeSat wizard

3. Results and discussions

The temperature data are recorded when the system reaches steady state as can be observed in Fig. 8. The recording is done at three different heat loads and three weight concentrations of the nano particles which are 0.25%, 0,5%, and 1% weight percentage of the working fluid.

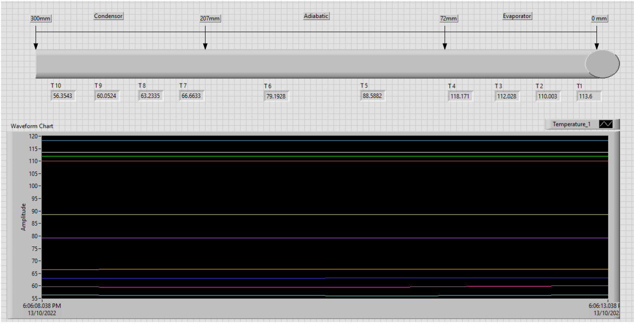

Fig. 8: LabVIEW monitoring window of the temperatures

The performance of the heat pipe is assessed by the temperature difference between the evaporator and condenser sides. Theoretically, a heat pipe must maintain a uniform temperature between its condenser and evaporator and transfer the heat through the phase change. Thus, the lower the temperature difference the better the heat pipe performs. As can be seen in Fig. 10, the temperature difference increases as the heat load increases which is directly proportional to the degradation that eventually compromises the performance.

In Fig. 9 the plots show ΔT for the cases without the addition/mixing of nanoparticles in the working fluid. Fig. 11. depicts the case of adding 0.25% wt nanoparticles and an improvement can be observed from the baseline case of without nanoparticles. This indicates the favorable effect in improving the heat transfer performance of the heat pipe which is attributed to enhancement in the conductivity of the mixture solution and the onset of nucleation.

The case of adding 0.5% wt of Al_2O_3 to water is depicted in Fig. 10. It shows an improved performance where the ΔT is the lowest at 5W and it increases at 10 W, however it decreases again at 15 W. Further increasing in the nanoparticle loading is shown in Fig. 12 at 1%. However, the further increase in the weight percentage leads to lesser performance potentials comparing with the 0.5% wt.

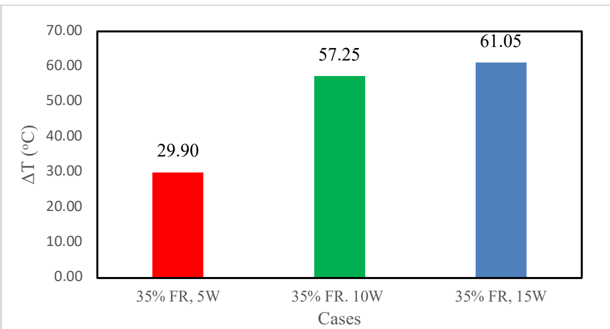

Fig. 9: ΔT of the cases without Nanoparticles

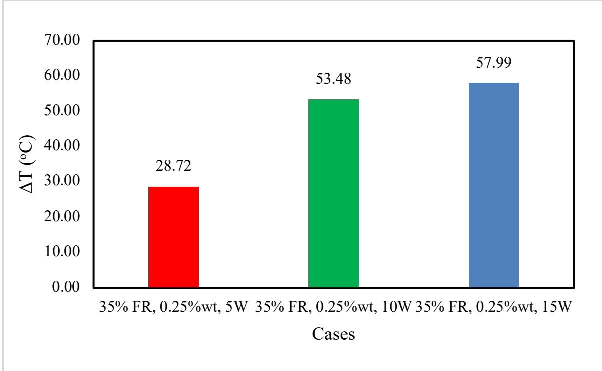

Fig. 10: ΔT of the cases with 0.25% wt Al_2O_3 Nanoparticle

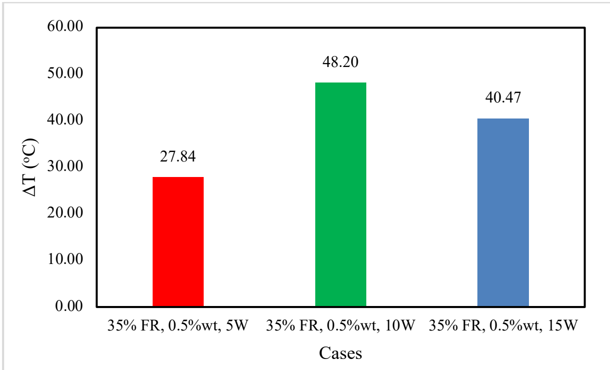

Fig. 11: ΔT of the cases with 0. 5% wt Al_2O_3 Nanoparticle

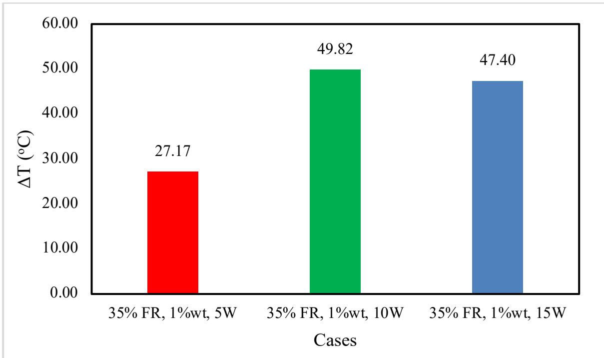

Fig. 12: ΔT of the cases with 1% wt Al_2O_3 Nanoparticle

Further sensitivity study done on the thermal resistance reveal additional insight to the heat pipe performance. This parameter can be calculated according to Eq. 4 as:

$$R_{th} = \frac{T_e - T_c}{Q_{out}} \quad (4)$$

Where T_e and T_c are the wall temperatures at the evaporator and the condenser, respectively.

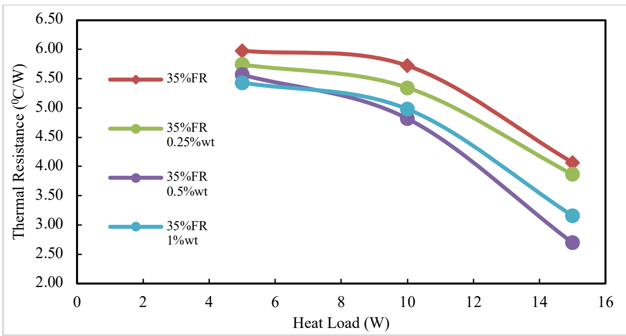

Fig. 13: Thermal resistance vs heat load for different cases

It can be seen from Fig. 13 that as the thermal resistance decreases the heat load increases which is a good indication. Specifically, the addition of nanoparticles at a concentration of 0.5%wt shows the best performance. Increasing the percentage of nanoparticles any further will revert back to low performance.

3. Conclusion

A sensitivity study was conducted on an Aluminum water grooved heat pipe to illustrate the effect of the performance degradation. This is always thought is due reaction of Aluminum with water at temperatures higher than 294 K. A heat pipe module then developed using metal 3D printing. The heat pipe was put to test at a filling ratio of 35% at three different heat loads. The system showed that as the heat load increases the performance of the heat pipe drops. An attempt was made to preserve the performance of the heat pipe if possible, using alumina nanoparticles. Three different weighting percentages were used, i.e., 0.25%, 0.5% and 1%. The addition of nanoparticles enhanced the performance of the heat pipe which was observed by monitoring the temperature differences between the evaporator and the condenser. Also, the thermal resistance versus the heat load was evaluated as another performance indicator. It is found that adding nanoparticles will enhance the performance and decelerate the degradation process. However, further increasing the weight percentage of the nanoparticles beyond 0.5% resulted again in performance degradation.

Nomenclature

R	Radius of the heat pipe
ΔT	Temperature difference between the evaporator and condenser of the heat pipe
T_e	Temperature at the evaporator wall
T_c	Temperature at the condenser wall
R_{th}	Thermal resistance
Q_{out}	Heat load subjected on the heat pipe

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