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Review on Development of Aluminium Water Heat Pipe

Harshit Panchal[1], Bhardhvaj Bariya[2], Krunal Labana[3],
Mr. Vishank Vasava [4]
[1-3]U.G. Student, Mechanical Engineering, Sigma Institute of Engineering, Bakrol, Gujarat, India
[4]Assistant Professor, Mechanical Engineering, Sigma Institute of Engineering, Bakrol, Gujarat, India

ABSTRACT

A common type of heat pipe used for computer cooling applications has been copper as a fluid container and water as a working fluid. The nature of copper such as high mass and material cost, however, has spurred considerable interest on aluminum as a potential replacement while aluminum-water combination is subject to corrosion reaction. In this paper, we present the technology development results attempted to enable the aluminum-water heat pipes. We studied an approach of providing thermodynamic compatibility between the aluminum surface and water by a formation of a defect-free hydration layer on top of the aluminum surface. Our trial of this technique applied to non-wick aluminum heat pipe samples revealed that the non-condensable gas generation can be effectively suppressed by the new coating structure evidenced by continuous working of heat pipe after a high temperature reliability testing of more than 300 hours at 130 °C. We also applied the same technique to wicked aluminum pipes and evaluated heat carrying capacity and thermal resistance.

Key words*:* aluminum, hydration, corrosion, non-condensable

1. INTRODUCTION

Heat pipes are an integral part of modern electronics device cooling as they enable effective cooling solutions. A common form of heat pipe for this type of application has been copper as a fluid container and water as a working fluid. This, copper-water heat pipe, offers many of desired heat pipe properties for device cooling applications. Among many, the most notable advantage of copper-water heat pipe stems from the fact that 1) it can carry far greater amount of heat per unit than any other heat pipes in relevant temperature ranges of electronic device cooling, and 2) it shows very little performance degradation; thanks to compatibility between copper and water.

While copper-water heat pipes are the industry standard for achieving high thermal performance, some drawbacks exist; 1) the high density of copper contributes to high mass thermal solutions while products are becoming smaller and lighter, and 2) in recent years the cost of copper has increased significantly, impacting the overall product cost in downward cost pressured industries. This has spurred considerable interest on aluminum as a potential replacement for copper heat pipes with a desire to cultivate its low-cost and lightness, in addition to many advantageous properties in terms of its processing; however, as B&K (Brennan and

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Kroliczek, 1979) and Chi (1976) summarized compatibility of variety of working fluid and container material combinations, aluminum heat pipe with water as a working fluid has never been realized in spite of numerous attempts in the past.

Aluminum is chemically incompatible with water and is subjected to corrosion reaction without natural inhibition. The generation of non-condensable gas resulted by the corrosion and thus breakage of internal vacuum makes the heat pipe to cease to function. Practical working fluids compatible with aluminum reported to date includes ammonia, ethane and freons. In reality, however, it is reported that trace amounts of water is considered to be problematic in aluminum-ammonia heat pipe because of formation of hydrogen gas (NASA, 1999). Several prior attempts to this problem, where a thick oxide such as anodized oxide is designed to cover the aluminum surface, fail to show any meaningful improvement as they do not stop reaction but only decrease the rate of reaction.

In this paper, we present development results toward solving key technical challenges and enabling the aluminum-water heat pipes.

2. MATERIALS AND TEST METHODS

2.1 Materials

In order to suppress hydrogen formation dramatically in an attempt to enable aluminum-water heat pipes, we chose an approach of providing thermodynamic compatibility between the aluminum surface and water by a formation of a defect-free hydration layer referred to as aluminum hydroxide, or Al(OH)3 on top of aluminum surface. To evaluate feasibility of this technique, we prepared two types of pipe forms with; 1) 6 mm O.D. Bare pipe without wick structure and 2) 6.35 mm O.D. Groove wick pipe as containers of water heat pipes. As shown in Table 1, we prepared three types of bare pipe samples for evaluating corrosion protection capability and long term reliability, and one groove pipe sample was made to test capability of heat pipes as a natural next step.

Sample A is made without hydration process and considered to be a representative of naturally formed aluminum oxide surface. Samples B and C are differed by changes in cleaning/hydration layer coating process. Sample D is made using groove pipe with again change in coating process to suit for groove pipe dimension.

Table 1: Heat pipe samples tested.

Sample	Coating	Pipe	Test
A	No coating	Bare	Reliability
B	Coating-1	Bare	Reliability
C	Coating-2	Bare	Reliability
D	Coating-3	Groove	Resistance

All the pipes before applying coating process have composition of 1000 series aluminum material which is widely utilized in the industry.

Overview images of aluminum-water heat pipe samples are shown in Figure 1. Although there are two types of pipe shapes shown, we focused on discussing test results of round-straight shape pipes in this paper.

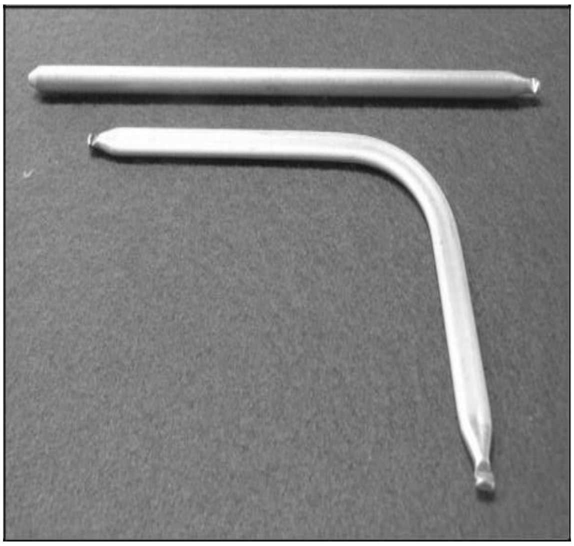


Figure 1: Image of fabricated Aluminum-water heat pipe samples.

Thickness of aluminum container was 0.5 mm for bare pipe. Groove pipe dimension was followings; fin height: 0.4 mm, base thickness: 0.6 mm and groove fin counts: 28. The groove pipe was selected from off-the-shelf air conditioning / heat pump applications as a trial. Therefore optimization of wick structures for water using aluminum material is not examined nor discussed in this paper.

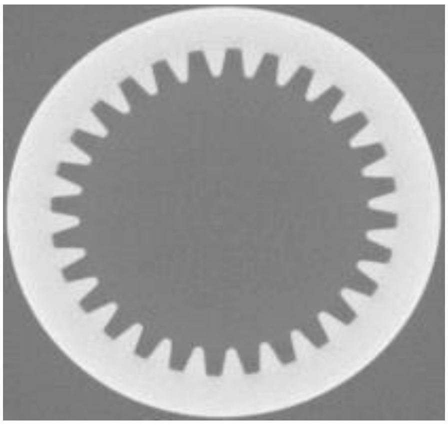


Figure 2: Cross section image of groove wick Aluminum-water heat pipe sample.

Mass of heat pipe is of the key interest for aluminum heat pipes. Weight of a 200 mm long, 6 mm O.D. pipe is measured as ~5 g and confirmed fabricated aluminum-water heat pipe measures approximately 1/3 of corresponding size of copper heat pipe which measured ~15 g as shown in Table 2.

Table 2: Mass of fabricated heat pipe in comparison to Cu heat pipe.

Heat pipe type	Length (mm)	Mass (grams)
Aluminum-water	200	~ 3.3
Cu-water	200	~10

2.2 Fabrication Process

Fabrication process of aluminum-water heat pipe in our study is shown in Figure 3. Although this process flow resembles that of copper heat pipes, key differences are the addition of chemical processes such as the first cleaning and the hydration layer coating processes.

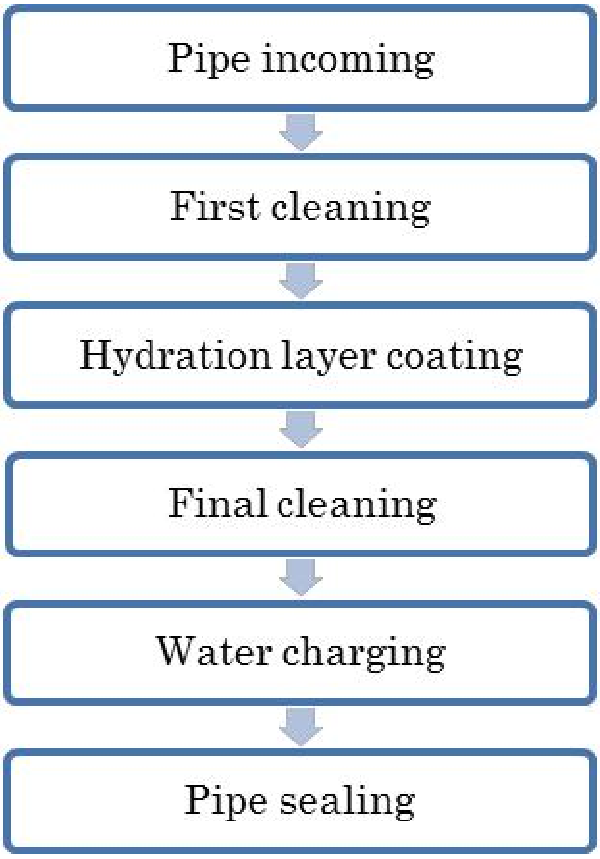


Figure 3: Aluminum-water heat pipe fabrication process.

The first cleaning process is designed to remove naturally made surface oxides in air, surface contamination from pipe manufacturing process, and impurities embedded in pipe materials in order to expose fresh aluminum. Hydration layer formation process is applied after the first cleaning step. We have utilized glass containers for both of these chemical treatment processes as shown in Figure 4 in this experiment. All of samples were made in 200 mm long form and six pipes were processed at one time using rack per batch.

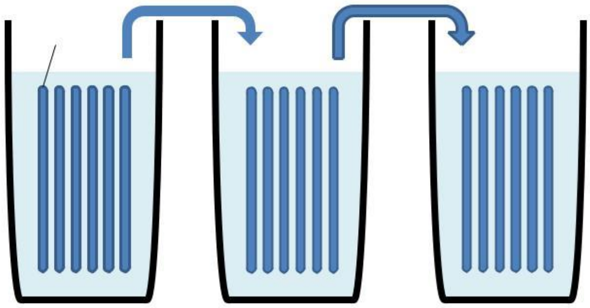


Figure 4: Experimental chemical treatment baths.

After the final cleaning process is done, water is charged and pipe ends are sealed using the processed aluminum container.

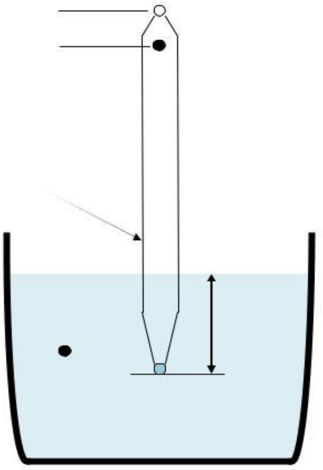
2.3 Test Methods

2.3.1 Hot Water Dipping and Accelerated High Temperature Test for Long Term Reliability

Firstly, functionality of fabricated aluminum-water heat pipes as a consequence of suppression of hydrogen is tested by hot water dipping method (Figure 5). We measured bare pipe heat pipe samples in a way that one fourth length from bottom of heat pipe is dipped into a hot water bath with controlled temperature at 60 °C. Temperatures of hot water (TW) and heat pipe (THP) are measured by thermocouples after waiting 2 minutes after dip and calculated Delta-T (Formula 1).

$$Delta\text{-}T = TW - THP \qquad (1)$$

In a case of non-condensable gas generation, the Delta-T value will be increased thus heat pipe functionality degradation is monitored in such a manner. For reference, Delta-T of working copper heat pipes is in a range of 2~5 °C.



The key reliability deterioration factor in aluminum-water heat pipe system is considered to be a progression of corrosion at high temperature conditions. We have set a reliability goal of Delta-T deterioration of less than 3 °C after accelerated high temperature tests of 300 hours in 130 °C, determined by hot water dip testing method described earlier. The goal is approximated to be less than 5 °C in absolute delta T value after roughly 20,000 hours of operation at 70 degrees with an assumption of 10 °C;2 times acceleration factor general rule.

In the course of the reliability testing, heat pipe samples are initially tested by hot water dip and stored in an oven chamber at atmospheric pressure at pre-determined temperature and duration of times shown in Table 3, taken out and tested by hot water dip in a same manner as reliability read outs. After the test, samples were stored back to the oven chamber until the next read out. To illustrate comparison, a read out at 70 °C after one hour was added only for Sample-A.

Table 3: Reliability test temperature and time duration.

Read out	Temperature (°C)	Duration (hours)
After fabrication	NA	NA
70C/24H	70	24
100C/24H	100	24
130C/24H	130	24
130C/72H	130	72
130C/144H	130	144
130C/216H	130	216
130C/300H	130	300

2.3.2 Thermal Resistance and Heat Carrying Capacity

Thermal resistance and heat carrying capacity of fabricated samples with groove pipes were tested with instruments shown in Figures 6 and 7. The heat pipe is coupled with a heater at the evaporator end, and a condenser side is connected to a cooling block/heat exchanger unit using thermal grease. The heat pipe is placed in a horizontal settlement.

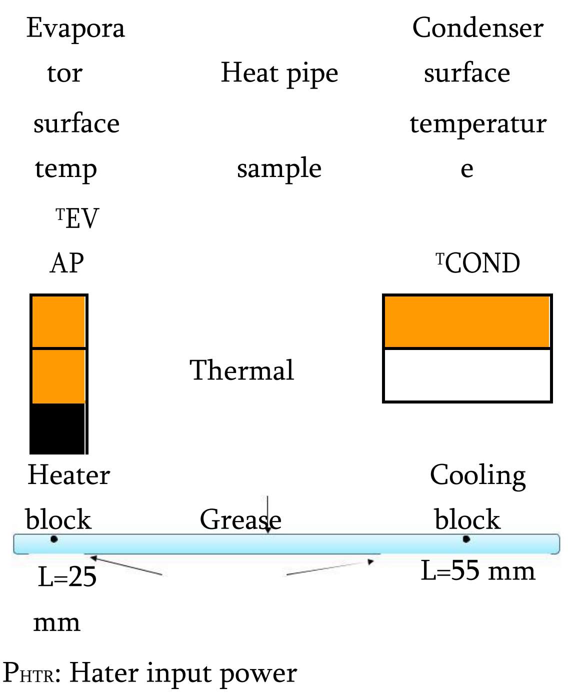


Figure 6: Illustration of experimental set up of thermal resistance and heat carrying capacity test.

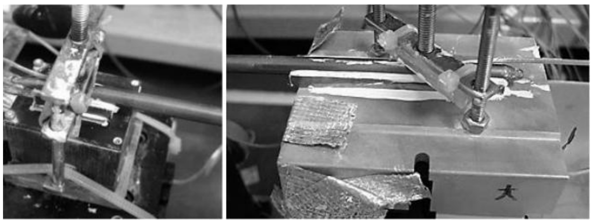


Figure 7: Picture of experimental set up of thermal resistance and heat carrying capacity test. Heater / Evaporator section is on the left and Condenser / Cooling block is on the right.

Temperatures of heater, heat pipe at evaporator (TEVAP), heat pipe at condenser (TCOND) and heater power input (PHTR) are measured and calculated thermal resistance (R) by Formula (2).

$$R = (TEVAP - TCOND) / PHTR \qquad (2)$$

The maximum heat carrying capacity of the sample was determined by curve turning point of thermal resistance dependency on power.

2.3.3 Coating Surface Characterization and Reliability failure

The surface of aluminum hydroxide layer is observed by SEM for determination of the coating quality and discussing failure mechanism of the aluminum-water heat pipes.

3. CHARACTERIZATION AND RESULTS

3.1 Hot Water Dipping and Accelerated Reliability Tests

Initial heat pipe function and accelerated high temperature reliability test results are shown in Figure 8. The very first observation in the test we noticed was a complete failure of Sample A with Delta-T increase of more than 20 °C after a mere one hour at 70 °C. Later it was found that heat pipes fabricated with same process are subject to stop functioning without applying elevated temperature condition as early as several hours.

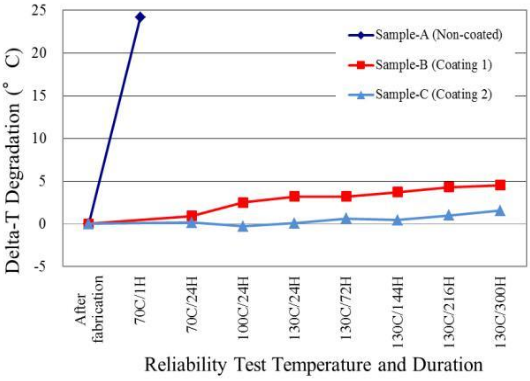


Figure 8: Experimental set up of thermal resistance and heat carrying capacity test.MeanwhileSample-A stopped continuing of reliability test, Sample-B demonstrated considerable level of improvement over non-coated sample, however 2.5 and 4.5 °C after 100C/24H and 130C/300H tests were recorded respectively. The curve suggests the sample had defects that initiate deterioration by experiencing the 100 °C environment, however degradation continued in slow manner afterwards.

In contrast, we did not observe noticeable degradation until 130C/144H period for Sample-C under condition of +/- 0.5 °C accuracy. The same sample continued to perform well and exhibited low level degradation toward the end of 130C/300H test with 1.5 °C Delta-T increase. The results achieved our initial reliability goal and considered to be sufficient for applications as long as the particular test method is concerned.

3.2 Thermal Resistance and Heat Carrying Capacity

In this section, thermal resistance measurement results and heat carrying capacity for groove aluminum-water heat pipe (Sample-D) is discussed.

In the beginning, Sample-D was applied with 10 W of heat and performed at 0.08 °C/W thermal resistance. As increasing the power input of the heater, thermal resistance was decreased to 0.05 °C/W at 30 W. The trend is comparable to Cu-water heat pipes tested in the same way and thermal resistance value at 30 W for Cu-water heat pipe reference was equivalent level as Sample-D within equipment error level. There is not enough data to discuss characteristics of Al-water heat pipes and differences over Cu-water combination, however we observed phenomena of alteration of the surface roughness by coating process parameters that potentially benefits of controlling wettability between container material and working fluid to further improve performance the Al-water heat pipes.

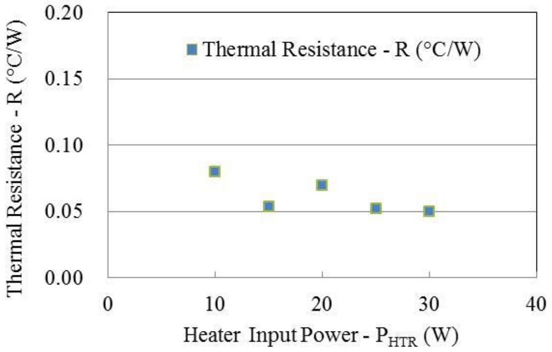


Figure 9: Thermal Resistance Test Results of Sample-D.

At next step testing at 35 W, the sample showed high level of thermal resistance as a result of rapid temperature increase at the evaporator, and testing was terminated compulsively without recording the stabilized data point. Thus we conclude the particular heat pipe sample had the heat carrying capability (PMAX) of up to 30 W or slightly higher, and this level of capability was in the vicinity of estimation from groove dimension which was not optimized for aluminum-water heat pipe application.

3.3 Coating Layer and Surface Characterization

Cross section image of hydration layer coated bare pipes is shown in Figure 10. The SEM image shows uniformly coated layer formation on top of the base aluminium.

Next, internal surface of the bare pipe sample was observed by SEM from the top view as shown in Figure 11. There are crystalline boundary like structure lines seen run from top-right to bottom left of the image. It illustrates the coating layer is formed uniformly without defects such as non-coating spots in the observed area.

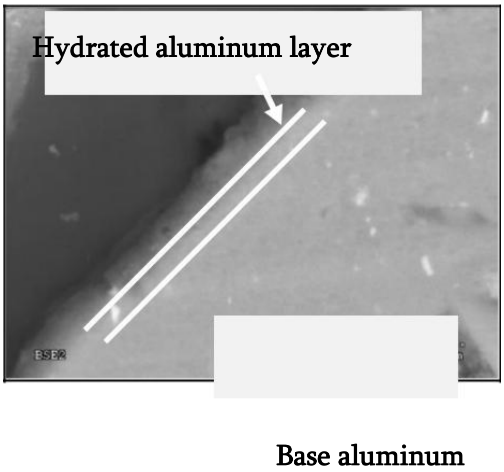
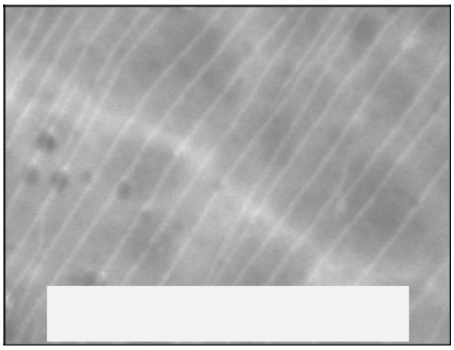


Figure 10: Cross section image of hydration layer coated aluminum.



Top view of coating surface

Figure 11: Top view of coating layer by SEM.

As evidenced in Figures 10-11, the hydroxide layer formed by the process was reasonably uniform and near defect-free. This made our heat-pipe to show an excellent resistant against corrosion-induced degradation of heat-pipe functionality. These results indicate that our approach is fundamentally correct and has a potential to be implemented for production heat pipes. Nevertheless, we observed a few areas that need further developments. Although the stability of aluminum-water heat-pipe is reasonably good, it is not perfect yet. We observed that there still existed a few spots where hydroxide was poorly developed and it was found to be the area where contaminants were persisted, most notably, contaminants in raw aluminum alloy. It is our conclusion that a better surface cleaning method is necessary to eliminate such contaminants in order to increase the stability of aluminum-water heat pipes against corrosion induced performance degradation. Also it is noted the fact that some of our initial process methods were not fully compatible with mass manufacturing. For more maturity, consistency, and compatibility to mass-production, further developmental efforts are necessary, some of which are currently in progress in our laboratories.

4. CONCLUSIONS

We described overview and results of aluminum-water heat pipe with hydration coating layer. As a result of our collaboration working group effort, significant progress has been made toward solving the key technical challenges to enable aluminum as a container material for water working fluid; improvement from negligibly short operation hour of non-coated aluminum pipe to over months of operation using our technique, repeatable thermal resistance performance comparable to copper etc. We conclude that the aluminum-water heat pipes with a novel approach have great potential in replacing copper-water heat pipes in product applications in the near future, and provide the benefits in the emerging cost and weight sensitive markets.

NOMENCLATURE

TW	Hot water bath temperature (°C)
THP	Heat pipe temperature in hot water dip test (°C)
Delta-T	Temperature rise of a heat pipe from hot water (°C)
TEVAP	Evaporator temperature of a heat pipe (°C)
TCOND	Condenser temperature of a heat pipe (°C)
PHTR	Heater input power (W)
R	Thermal resistance of a heat pipe (°C/W)
PMAX	The maximum heat carrying capacity (W)

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Our Review :

This rewiew paper gives help in decieding materials and working fluids for heat pipes for better heat transfer rates.

This rewiew paper gives help in improvement of heat transfer rates with the use of different materials and working fluids.

This review paper also give idea about scope of heat pipes in elecronics cooling.

This review paper also give knowledge about heat pipes working procedure.