ENHANCING HEAT TRANSFER RATE BY INTERACTION OF WATER - LIQUID METAL INTERFACE SURFACE

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ABSTRACT

Motivated with the continuous demand of having efficient cooling techniques to keep up with the incessant development of electronics and consequently the increased rate of their heat generation. The enhancement of the heat transfer rate of water as a prime coolant which is used in many thermal management applications became an area of study of many researchers. The present work experimentally studied the enhancement of heat transfer of a low thermal conductivity coolant (water) interfacing with another high thermal conductivity material, such as liquid metal (Gallium). For a variable volume ratio defined as the ratio of the Gallium volume to the water volume, the rate of cooling heat transfer is observed. Taking place by monitoring the temperature cooling for both coolants to room temperature. The study covers a range of volume ratios from 0 to 4 in steps of 1.0. The results suggested an enhancement of the heat transfer rate directly proportional to the increase of the volume ratio for both, constant water volume and constant Gallium volume.

INTRODUCTION

It became a necessity to come up with a highly effective and innovate cooling approach which can handle the demands of having a high performance electronic devices such as a computer processor, LED, and other miniature electronic applications which are very small in size but generate high density levels of heat.

The use of liquid metal as a coolant is a promising and effective solution to meet the cooling requirements of high heat flux devices such as electronic components. It was noted that liquid metal or its alloys can be used as a coolant that could significantly decrease the temperature of such applications. Among all liquid metals, gallium and its alloys are widely proposed to be used as coolants. In addition to their excellent thermal properties, they have the ability to be pumped efficiently by a silent, non-moving pump. Gallium has a low melting point, a high thermal conductivity, it is non-flammable and non-toxic, it has low vapour pressure, and a high boiling point.

It is important to note that water is still being used as a coolant for a wide range of electronic cooling systems. In this study a secondary stationary coolant (Gallium) is planned to be used in a cooling scheme by interfacing it with a primary coolant (water), what is proposed in a cooling scheme the Gallium is introduced in its solid phase, taking advantage of it is high heat of fusion (latent heat) as a heat sink, to cool down the hot circulated water (coolant) so it can be effectively reused in the cooling loop.

In coming few paragraphs a review of some of the most recent papers addressing similar applications will be presented.

Al Omari et al (2013); [1] experimentally studied the enhancement of the heat transfer rate of low thermal conductivity coolant (water) when interfaced with high thermal conductivity liquid metal (Mercury). Results show major improvement in the heat transfer rate of water. The study emphasizes that the dominant effect on the heat transfer rate enhancement is the surface area of the interface between the two fluids not the volume of the Mercury itself.

The author presented [2], the effect of co-flowing high thermal conductivity liquid metal (Mercury) to flowing water in direct contact. The results shows the used configuration has an pronounced effect on the heat transfer performance of water. This effect was related to the fact that there is a large temperature gradient generated in the interface between the two flowing fluids.

David et al (2013); [3], numerically studied a 2D and 3D model of a rectangular container filled up with Gallium as the sides were heated. The study focused on the Gallium solid-liquid interface, considering the variation of thermal properties during the phase change process. They also experimentally traced the liquid–solid interface position, profile and melt velocity using the ultrasonic Doppler velocity measurements in the liquid phase. Numerical results compared with known published results and the new data obtained in the present study, a better agreement between the experimental data and the 3D model were observed.

Different researchers study the usage of liquid metal in cooling systems for emitted diodes [4], and they compared their results to the case of using pure water. The results demonstrated better performance of using liquid metals. In one other application [5] they used liquid metal in a cooling system to dissipate the generated heat from an electronic application (CPU). The authors used two different configurations for the cooling system. It was reported that using liquid metal enhanced the heat transfer compared to the case of using liquid water. The capabilities of the MEMS based micro cooling devices using Gallium was investigated numerically by [6], the study concluded that the liquid metal based MEMS cooler has potential applications in harsh environments.

A paper by Mikityuk et al.; [7] addressed the thermal properties, cooling performance and pumping methods for different liquid metal coolants and the potential of using them in cooling applications. Due to the their capabilities as superior coolant mediums, the authors suggested they will be widely used in the nuclear industry and that they would be adopted in chip cooling on a large scale in the near future.

New correlations of heat transfer using different liquid metal were derived for heat exchange applications [8]. The correlations can be used to help select the heat transfer models for designing complex systems cooled by liquid metals.

The presented study addressed the effect of the overall rate of heat transfer using different volume quantities of both coolants water-Gallium while keeping the same interface surface area.

EXPERIMENT SETUP

In this section a full description of the experimental setup is presented. A certain amount (volume) of liquid gallium was poured in an acrylic cup. After the gallium was fully solidified, hot water was poured on top of the solid gallium in direct contact and allowed to cool down to room temperature. The cup was placed above a large water bath so that the base of the cup was immersed in the water while the rest of cup body is in contact with the surrounding air. The cup is made of acrylic, is a cylinder with 3 mm wall thickness, the cup's outer diameter and height are 90 mm and 52 mm respectively, the cup's acrylic top cover thickness is 6 mm. The cup has a 10-mm thick brass base, it is used to control the boundary condition of a constant base temperature of 22^o C. Fig. 1 shows the experimental setup used. Nine K-type thermocouples were used to capture the real-time temperature history at specific positions. The K-Type IMO-TC-150 which is made by Omega, the manufactured thermocouple's accuracy is ±0.5 ^{o}C. The position of each thermocouple and the setup component of which the temperature was measured was listed in the same figure. All of the thermocouples were connected to a data acquisition device (type cNDAQ 7867 from National Instrument) in order to log the temperature measurements as a function of time on a PC using LabVIEW.

The experiments were divided into 4 groups according to the volume of the water. Each group consisted of 9 cases for 9 different gallium-to-water volume ratios. The first case in each group of experiments (pure water) was used as a reference case for that group, where water was placed alone in the cup and allowed to cool down with the absence of gallium. One case is presented in this paper.

A summary of the presented cases are summarized in Table 1, where the water volume is kept constant, and the volume ratio changed by changing the Gallium volume, the volume ratio is defined as Gallium volume divided by the water volume. For the case of constant water volume of 60 ml and the Gallium to water volume ratio varied from 0 to 4 in a step of 1.0. Also, the study reports the results of a case with a constant Gallium volume case for Gallium to water volume ratio ranged from 1 to 3. In all cases the water is added to the system at a fixed temperature of 70^{o}C on top of the solid Gallium which initially is at the temperature of 22^{o}C.

Table 1. Case Study

$VR=V_{Ga}/V_W$	0	1	2	3	4
V_W=60(ml) & V_{Ga} (ml)	0	60	120	180	240
Case #D	1D	3D	5D	7D	9B

RESULTS AND DISCUSSION

In this section a sample of the results is presented and discussed. In order to determine the number and the location of the thermocouples used, a prior experiment is conducted to study the radial dependent of the temperature measurements performed, the results demonstrate that the temperature is independent of the radial variation for the water and the Gallium, the percentage variation of data at one location shows a percentage standard deviation of 0.2%, which may be related to the size of the used cup being small during this experiment. Based on these results, one temperature measurement is taken at the centre of the water and the Gallium's volume is measured for all vertical locations. Figures 2 shows the time history of water temperature and Gallium temperature. Figure 2-a shows the time dependent of the water volume-temperature measurement. The time history captured the temperature drop starting with the initial temperature around 70^o C until it decreases to room temperature. Volume ratio of 0 represents the referenced case of pure water, which is used for comparison purposes. The results demonstrate different rates of heat transfer for different cases of volume ratios, this change in heat transfer rate is captured in Figure 4. For the case of volume ratio of 4, suggests the highest rate of heat dissipation compared to all other cases, including the referenced cases.

Figure 2-b shows all the curves that indicate the time history of Gallium's temperature measurements at the centre point of Gallium's volume, which is initially at 22^{o}C before adding the hot water. The shown curves display the behaviour of Gallium's temperature where initially it gains energy, and the Gallium's temperature increases to an average of 35-45^{o}C then it drop at different rates to reach the equilibrium condition of the ambient temperature, which suggests that the heat is dissipated to the boundaries and the surrounding.

Figure 3 shows all the curves that display the transient total rate of heat dissipation of the water and the Gallium. In all reported cases the least heat rate dissipated was noticed for the referenced case with volume ratio of zero. This clearly proves that interfacing the water with Gallium suggests a promising technique of have a more efficient heat sink for the conventional coolant (water). Different cases yielded a different response, this effect is captured in Figure 4.

Figure 4-a presents a summary of the performance of all studied five cases. The performance is expressed by monitoring the time interval required for the temperature to drop 20% of the peak temperature value; curve (a), and for the second time interval required for the temperature to drop 20% of second temperature; curve (b) respectively. Solid symbol shows the reference case of zero volume ratio. The reference case depicts the maximum time interval within the same group of the constant water volume. In curve (a) for the studied case a 10% to 30% time interval drop were realized respectively. In general, the trend is the decrease in time interval for the temperature drop as we increase the variable volume ratio. In graph (b) for the same case a 20% time interval drop.

Figure 4-b depicts a summary of the enactment of all the studied cases as Gallium volume is constant with variable water volume values. The performance is expressed by monitoring the time interval required for the temperature to drop 20% of the peak temperature value; curve (a), and for the second time interval drop of 20% of the second temperature; curve (b). Each symbols demonstrate a constant Gallium volume for variable volume ratios by changing the water volume. In curve (a): for the case of 60ml Gallium a 10% to 30% time interval drop was noticed. In graph (b): for the same case a 20% time interval drop. For both time intervals, it can be seen clearly, for a constant Gallium volume, that it decreases as the volume ratio increases.

CONCLUSION

In this work, the effect of a fixed interface area between high conductive liquid metal and a lower conductive coolant (water) for different volume ratios are presented. The effect of constant water volume with variable Gallium volume ratios and the effect of constant Gallium volume with variable water volume ratios on enhancing the heat transfer rates are illustrated. The results of this study can be summarized by the following findings:

- The heat removal rate from water is significantly enhanced due to the presence of the liquid metal (gallium) in direct contact with the water.
- The gallium-to-water volume ratio is not necessarily the dominant factor to enhance the heat transfer performance, but the presence of a minimum amount of solid gallium during the heat exchange process is.
- The cooling rate is enhanced by an average of 30% based on the time needed for water to drop 10 ºC from its initial temperature in all cases.
- In general, the trend is the decrease in time interval for the temperature drop as we increase the variable volume ratio.
- A farther investigation is needed to address the direct effect of the interface and the role it plays in the heat transfer rate enhancement process.

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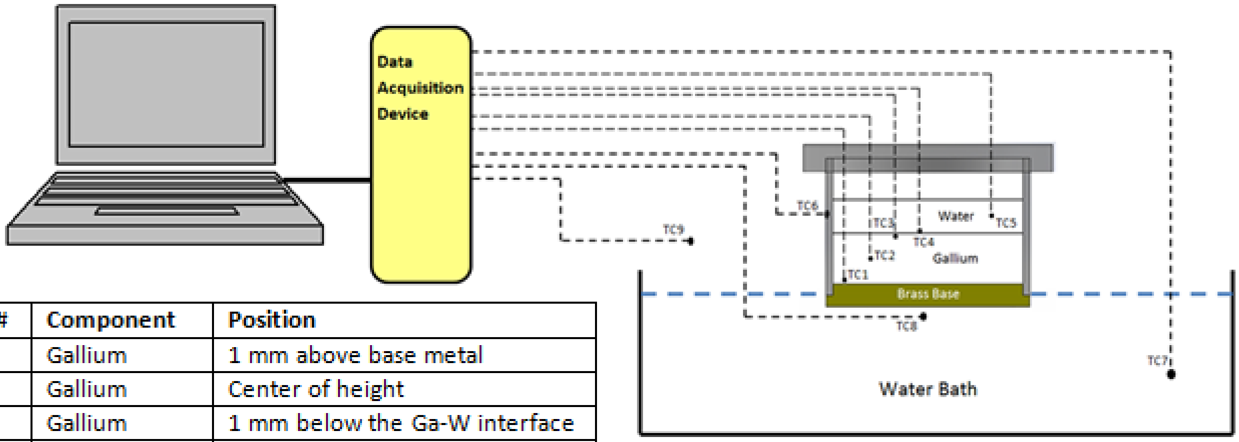

T/C #	Component	Position
TC 1	Gallium	1 mm above base metal
TC 2	Gallium	Center of height
TC 3	Gallium	1 mm below the Ga-W interface
TC 4	Water	1 mm above the Ga-W interface
TC 5	Water	Center of height
TC 6	Cup Surface	Water region
TC 7	Water Bath	Far from the cup base
TC 8	Water Bath	Near the cup base
TC 9	Ambient Air	Far from the cup surface

Figure 1. The schematics of Experimental platform

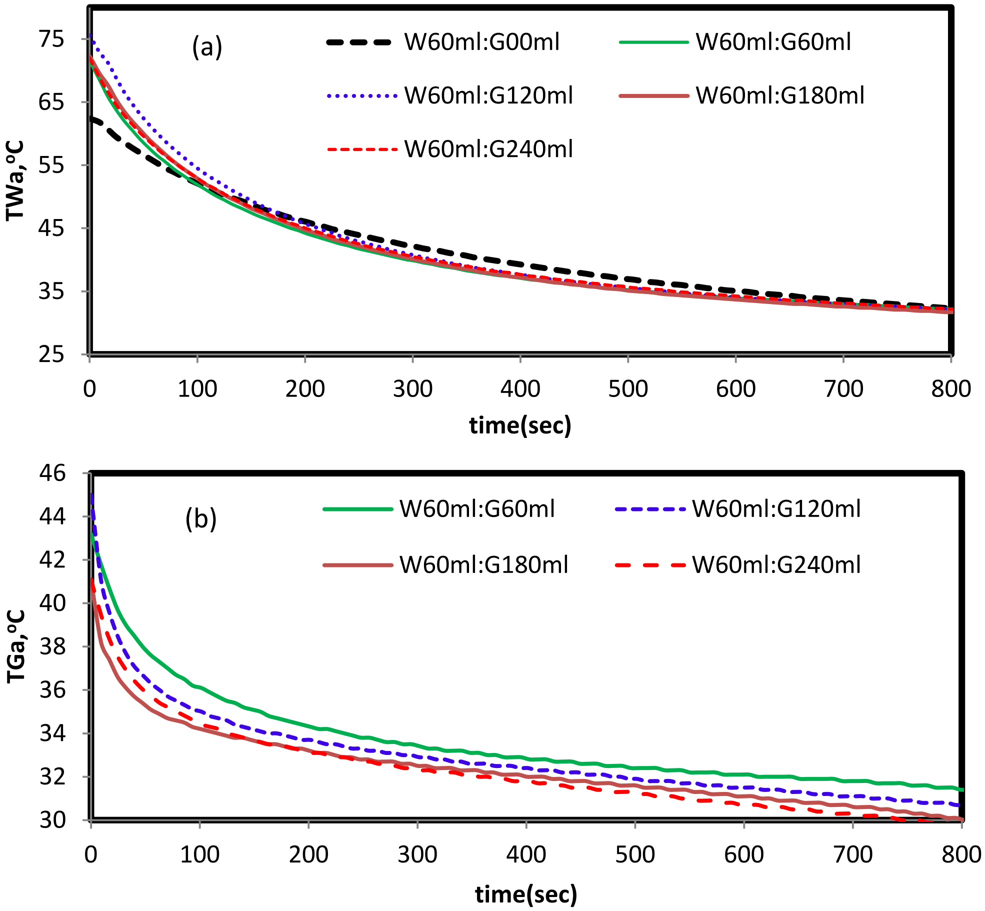

Figure 2 The temperature measurements vs. time (a) centre of the water volume (b) centre of the Gallium volume

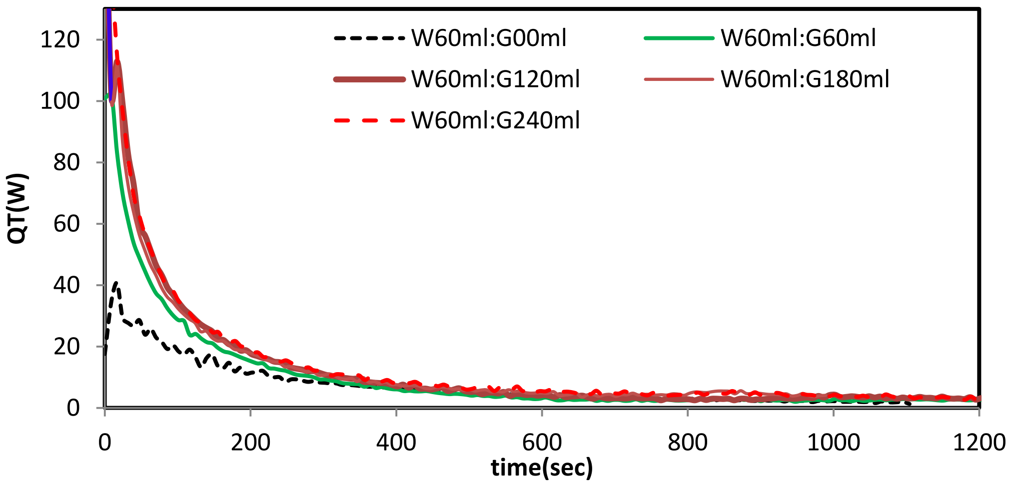

Figure 3 The total dissipated heat transfer rate vs. time

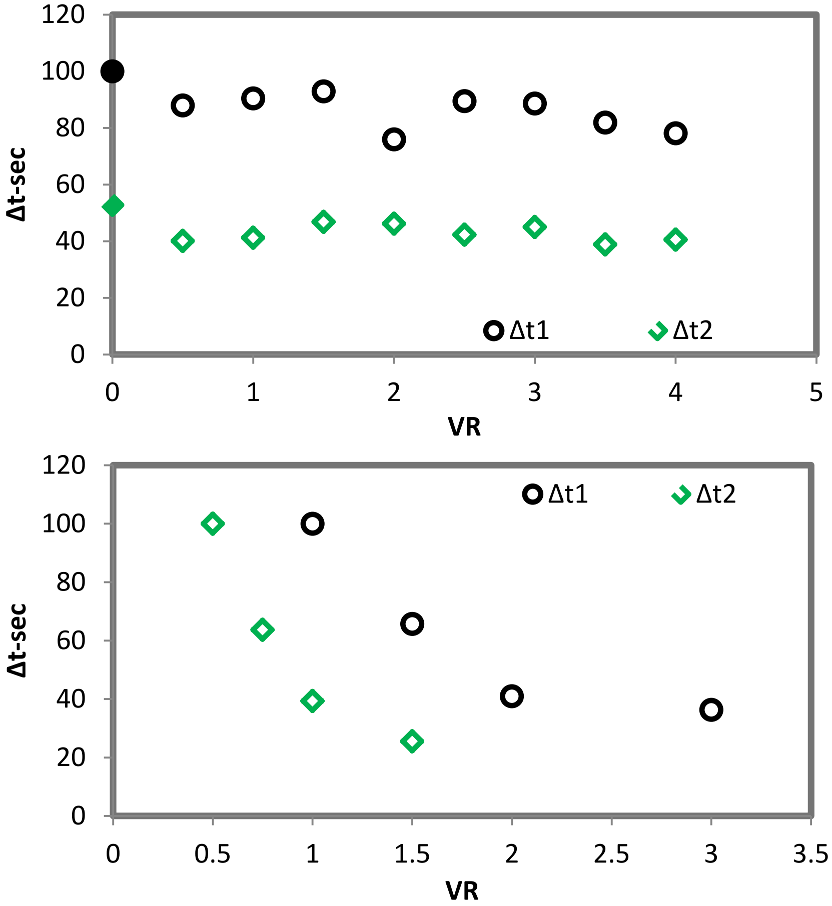

Figure 4 The time period required to drop the system’s temperature for different constant water volume case for (a) 20% of peak value temperature and (b) 20% of the of 2nd temperature interval.