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Experimental assessment of a direct-contact heat exchanger bubbling hot water in a cooler liquid gallium bath

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ABSTRACT

A direct-contact compact heat exchanger to enhance cooling of hot water, has been manufactured and tested experimentally. Hereby hot water is dispersed into a cooler liquid gallium bath in the form of small water bubbles emanating from 48 holes with 3 mm diameter each, drilled on four horizontal bubbles distribution tubes. Heat transfer limitations posed by gallium's low specific heat have been circumvented by imbedding cooling water tubes within the gallium. Thereby it was possible to maintain gallium at almost 30 °C during water bubbling; slightly above gallium's freezing point. Temperature reduction by about 23 °C was possible for hot water flow with initial temperature of about 60 °C and flow rate of 11.3 g/s when bubbled through such gallium bath that has temperature of about 30 °C and thickness of about only 18 mm. To realize such temperature drop for water using equivalent shell-tube heat exchangers of conventional kinds with 3 mm diameter tubing, a tube length in the range of 70 to 80 cm would be required. Theoretical considerations and empirical correlations dedicated to solid sphere calculations have been used to predict motion and heat transfer events for water bubbles moving through isothermal gallium bath. The computations were extended to include the experimental temperature conditions tested. Computations agree very well with experimental results.

1. Introduction

Heat transfer enhancement is so vital for many modern heat transfer applications such as electronics cooling. For example, it is essential for computers to be able to process more data in less time while still being compact in size [1]. This would entail the need for more power input and consequently more heat generation is expected of future electronics [2–3]. In the past, overheating of computer CPUs meant only failure. Currently, overheating may also mean an unacceptably slow operation where much decline in the CPU performance results from operating at temperatures above design limits [4].

As such, there is an urgent need to come up with unconventional means of heat exchange that can cope with the new trends and the increasingly more and more stringent requirements. Some of these requirements could be found in [5–9]. Traditional means of cooling are no longer capable of meeting the above constraints of compactness along with the high heat flux removal needs. For instance, air-based cooling systems have limitations due to the low convective heat transfer coefficient that cause using other heat transfer fluids to be a necessity [10].

When, for example, liquid water is used to cool the heat generation components in a heat application system, e.g. an electronics chip, it is either the heated water can be used in other heating applications; energy reuse [11–12], or it can be re-cooled down once again to be recycled back to the heat generation component for repeated heat removal process. Currently, bringing the cooling fluid to its initial temperature after capturing heat from the to-be-cooled heat source is accomplished by traditional heat exchangers of different kinds. For instance, exchangers that are based on some tubing arrangements or on flow configurations through which the hot to-be-cooled fluid flows while exchanging its heat with a cooler media through an intervening solid barrier (e.g. tube wall or the surface of a solid metallic plate). An example of the above arrangements and heat exchange configurations could be found in [13].

This study proposes a heat exchange concept to cool down hot fluids (e.g. hot water) without the need for a solid barrier separating the two fluids exchanging the heat. This concept capitalizes on the heat enhancement possibility by directly contacting the two fluids exchanging heat and by so doing the thermal resistance to heat transfer will be minimized. There is quite clear evidence already [14–16] gathered by both experimental as well as theoretical investigations showing that when two immiscible fluids exchange heat in direct contact, the heat transfer between them will be clearly faster than when they exchange the heat while being separated by a tube wall or a solid plate. This

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Nomenclature

A	bubble projected frontal area normal to the direction of bubble motion (m^2)
A_s	Surface area of spherical bubble (m^2)
a	Bubble's acceleration (m/s^2)
C_D	Drag coefficient
D	Bubble's diameter (m)
F_B	Buoyancy force (N),
F_D	Drag force (N)
g	Gravitational acceleration (m/s^2)
h	Convective heat transfer coefficient ($W/(m^2 \cdot K)$)
k	Gallium's thermal conductivity ($W/(m \cdot K)$)
m	Bubble's mass (kg)
Nu	Nusselt number
Pr	Prandtl number of gallium
$\dot{Q}$	Rate of heat removed from water bubble (W)
$\dot{Q}_{hw}$	Rate of heat removal from hot water (W)
Re	Reynolds number
T_s	Bubble's surface temperature (°C)
T_∞	Free stream temperature of the gallium away from the bubble (°C)
V	Bubble's velocity (m/s)
v_w	Bubble's volume (m^3)
W	Bubble's weight (N)
μ_g	Gallium's dynamic viscosity (Pa·s)
ρ_g	Gallium's density (kg/m^3)
ρ_w	Water's density (kg/m^3)

superiority is not only due to the fact that thermal resistance is being minimized in the case of direct contact, but also, possibly due to the enhanced intermolecular activities taking place in the interfacial region between the two immiscible fluids while exchanging heat. This heat transfer enhancement becomes even more pronounced when using a high thermal conductivity fluid such as a liquid metal (e.g. liquid gallium) to act as the heat sink media in the proposed direct-contact heat exchange process.

The heat exchanger design presented in this work builds on the above arguments and observations and, consequently, comes up with even further improvements and capitalizations on the above merits of direct contact heat exchange. More specifically, it utilizes the following effects: (1) the buoyancy forces that will be acting on the hot fluid bubbled through a denser liquid heat sink material (here liquid gallium) and the associated vigorous motions and turbulent effects, and (2) the enhanced direct heat exchange with cooler and high thermal conductivity surrounding sink material (gallium) when disintegrating the to-be-cooled fluid into small bubbles; thereby, significantly increasing their contact area with the sink material.

Different previous studies considered the bubbling of gases into a liquid media, as well as the two phase flows of liquids with different densities (see for example [17–23]). However, to the best of the authors' knowledge, limited works (if any) have addressed the bubbling of a liquid such as water into liquid gallium with the purpose of enhancing heat exchange between the two of them. In general, there is very limited research on the bubbling of lighter fluids into liquid metals. Among these limited works are references [18,19,22] which considered the bubbling of gases into liquid metals of different kinds.

2. Theoretical aspects and mathematical formulation for preliminary bubble computations

Due to the lack of specific correlations dedicated explicitly for water bubbles moving and exchanging heat with a liquid metal bath, we will perform computations in this study based on theoretical considerations and some empirical correlations that are obtained specifically for heat transfer from solid spherical particles moving through a fluid media. The empirical correlation used for convection heat transfer calculations cover a wide range of particle's motion conditions that includes the Reynolds number range encountered by the bubbles in this work and a range of Prandtl number values for bath material that includes the liquid metal used here namely liquid gallium. Computed results based on solid sphere's correlations may not be an exact fit for the case of the liquid water bubbles dispersed in gallium. Yet, given the lack in the literature of explicit correlations for water bubbles in liquid metals-like fluids, the performed computations are still expected to give some useful insight and guidance for understanding the experimental results obtained for water bubbles and would help interpreting them. The obtained experimental results for the water bubbles in gallium and their possible deviations from the computed results, might also help coming up with new empirical correlations for the bubbles case that would enrich the literature in this important area.

For the computed results, we consider hot spherical water bubbles that start their motion at the bubbling orifice from zero speed and accelerate upwardly due to net force caused by buoyancy effects. The density ratio of the gallium to water is about 6. Hence, this will cause the bubbles, once they detach from the bubbling orifice rim, to begin their acceleration at a 5 times faster rate than gravitational acceleration before they attain their terminal velocity. The initial bubbles' temperatures considered in the carried out computations are comparable to the initial temperatures encountered in the experimental runs conducted namely 50 °C and 60 °C.

Fixed gallium bath reservoir temperature values are considered for the performed computations; 30 °C, 40 °C, and 50 °C. These values are selected in such a way to reflect the impact of gallium bath temperatures on the cooling rate of water bubbles as well as on the minimum amount of gallium height that would be required to cause a certain temperature drop for the bubbles during their trip through the gallium.

A range for the bubble diameter from 1 mm to 4 mm has been selected for the computations. In the conducted experiments the bubbling orifice diameter is made to be 3 mm. The bubble size at the moment it detaches from the bubbling orifice would be decided by interplay action of different forces including buoyancy, surface tension, gravity, and pressure forces at the bubbling tube. By conducting simplified calculations for the bubble size at the moment of detachment from the bubbling orifice, one can conclude that the bubble emanating from the 3 mm-diameter bubbling hole would be approximately in the diameter range of 4 to 5 mm.

Fig. 1 presents a free body diagram for a spherical particle. The motion of this spherical solid particle in the surrounding liquid gallium bath is characterized by Newton's second law:

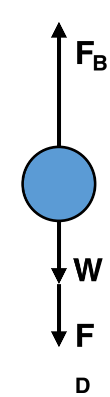

Fig. 1. Free body diagram of the spherical bubble.