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An experimental study on natural convection heat transfer of liquid gallium in a rectangular loop

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ABSTRACT

In the present study, the natural convection heat transfer of liquid gallium is investigated in a rectangular loop which consists of an indirect heating block test section for heat transfer rates, 1/2" tubes and a condenser as well as an orifice for measuring flow rate. The mass flow rate for natural convection and average Nusselt number of liquid gallium were measured within the heat flux range of 6.17×10^3–5.07×10^4 W/m^2. The measured heat transfer rates were correlated as follows: $Nu_D = 0.745 + 0.004Ra_D^{0.033} \approx 0.75$, corresponding to laminar natural convection regime. Also, the flow rates for the natural convection of liquid gallium depending on power level were also compared by using a CFD code and MARS-LMR (Multi-dimensional Analysis of Reactor Safety) code. The MARS code was modified into so-called MARS-Ga applicable for gallium-cooled systems in terms of physical properties. It was found that the predictions were in good agreements of the trend with the experimental results.

1. Introduction

The knowledge of the natural convection heat transfer in liquid gallium is important for an understanding of natural convection phenomena in liquids with low Prandtl numbers. Gallium belongs to Group III of the periodic table of the elements and properties are as shown in Table 1 [1,2]. The melting temperature of liquid gallium is close to the room temperature, while its boiling temperature is about 2477 K. This is a prominent feature of gallium among various candidates for liquid–metallic coolants of nuclear applications [3]. Natural convection is a buoyancy-driven fluid motion that is able to function without electric power or actuation by control equipments. The natural convection-driven system provides several benefits such as simplicity, reduction of the cost and no usage of cooling pumps. In nuclear engineering, the so-called passive heat removal systems using natural convection play a key role for nuclear safety.

Therefore, this study aims to experimentally investigate the heat transfer characteristics of liquid gallium in a rectangular loop under natural convection to secure experimental data of liquid gallium that are usable to the passive cooling systems of nuclear power plants or other liquid metal applications. Of course, although there have been many experimental data of natural convection in non-metallic fluids such as water, liquid metals such as sodium, LBE(Lead–Bismuth eutectic) are few and those of gallium are fewer compared to other liquid metals. There are several previous studies for the natural convection experiments that use liquid metals and gallium. Hata et al. [4] obtained systematically the experimental data of natural convection heat transfer from a horizontal test cylinder in liquid sodium for Rayleigh number ranging from 41 to 25,650 and examined whether the experimental results can be described and compared using existing correlations. Jackson et al. [5] presented a theoretical model that was influenced of buoyancy on turbulent heat transfer to liquid sodium flowing in a vertical pipe. In this work, the equations for laminar and turbulent free convection to liquid sodium were obtained. Davies et al. [6] described the sodium natural convection (SONAC) experiment for studying natural convection from a flat heater plate immersed in a sodium pool which can be inclined from the vertical to the horizontal with the heat flux in a downward direction. The experimental correlations for a horizontal position and 15°-inclined position in sodium were obtained. Borgohain et al. [7] carried out not only the steady state natural circulation experimental studies of Lead Bismuth Eutectic (LBE) loop for different power levels but also transient studies for start-up natural convection, loss of heat sink and step power change in the loop. This study developed a 1D code named LeBENC to simulate the natural convection characteristics in closed loops and conducted validation of the LeBENC code with the experimental data and the results showed good agreements.

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Nomenclature

A	heat transfer area (m^2)
C_n	fcc Madelung constant
C_p	specific heat (J/kg K)
C_R	heat transfer coefficient (W/m^2 K)
D	diameter (m)
E_{coh}	cohesive energy (J/kg)
Gr	Grashof number
Gr^*	modified Grashof number, $\frac{D^3\rho^2\beta gQH}{\mu^3 AC_p}$
H	height (m)
L	characteristic length (m)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
m	parameter
N	atomic weight (kg/mol)
N_G	geometric parameter
Nu_L	Nusselt number for common immersed (external flow) geometries, $\frac{hL}{k}$
Nu_D	Nusselt number for cylinder (tube), $\frac{hD}{k}$
Nu_m	Nusselt number (mean value)
n	parameter
P	pressure (Pa)
Q	multiplier
q	total heat (W)
R	flow resistance parameter
Ra_L	Rayleigh number for common immersed (external flow) geometries, $\frac{g\beta(T_{surface}-T_{fluid})L^3}{\upsilon\alpha}$
Ra_D	Rayleigh number for cylinder (tube), $\frac{g\beta(T_{surface}-T_{fluid})D^3}{\upsilon\alpha}$
T	temperature (K)
V	specific volume (m^3/kg)

Greek symbols

ρ	density (kg/m^3)
μ	viscosity (kg/m s)
β	coefficient of volumetric thermal expansion (K^{-1})
α	thermal diffusivity (m^2/s)
$\sum_a$	macroscopic absorption cross section (m^{-1})
λ	de Broglie wavelength (m)
ε	parameter (J/atom)
σ	parameter (m^3/atom)
v	kinematic viscosity (m^2/s)

Subscripts

a	absorption
av	average
B	buoyancy
b	boiling
eff	effective
f	friction
in	inlet
l	liquid
m	modified
out	outlet
ss	steady state
0	reference

Ma et al. [8] designed and constructed the test facility to investigate the thermal hydraulic characteristics of LBE. The experiments showed that the maximum flow rate for the natural convection was ~0.5 kg/s, resulting in heat removal of ~15 kW from the core tank. The analysis performed with the RELAP5 code is in reasonable agreements with the results.

The circumferential distribution of the Nusselt number for mercury was reported by Michiyoshi et al. [9]. This work presented the experimental data of natural convection heat transfer from a horizontal cylindrical heater immersed in mercury pool with the magnetic field and without the magnetic field. From experimental results, magnetic field affected local heat transfer coefficients and the local Nusselt number decreased with increasing the Hartmann number. Two-dimensional convection of liquid metals below an infinite strip and axisymmetric convection below a circular plate was computed for a uniform surface temperature and for a uniform heat flux in Schulenberg [10]. The local Nusselt number was correlated with the Grashof and Prandtl numbers and it was predicted to be higher than those previously achieved with integral methods but agreed better with experiments. Sugiyama et al. [11] clarified the heat transfer characteristics of natural convection around a horizontal circular cylinder immersed in liquid metals. This paper presented numerical results by using the Boussinesq approximation compared to existing experimental data for several liquid metals.

Table 1
Relevant physical properties of liquid gallium.

	Relevant physical properties
ρ (kg/m^3)	6330–0.7717 T
μ (kg/m-s)	0.01207–5.754 × 10^{-5} T + 7.891 × 10^{-8} T^2
β (K^{-1})	0.7717/ρ
k (W/m-K)	−7.448 + 0.1256 T

Hurle et al. [12] reported an experimental study of the occurrence of temperature oscillations in liquid gallium contained in a rectangular boat and heated from the side. This work indicated that the period of temperature oscillations increased as increasing boat length rather than depth and decreased as the effect of a transverse magnetic field. Additional result for this was provided by the fact that the onset of oscillations does not produce a significant increase in the Nusselt number. Mohamad et al. [13] attempted to combine experimental and full numerical simulations to gain improved understanding of some aspects of the flow and natural and mixed convection in a shallow rectangular cavity filled with liquid gallium. Temperatures were recorded at different locations in the cavity and temporal variation of the temperatures was analyzed. The results showed that lid motion had a significant effect on the flow and thermal structures in the cavity. Derebail et al. [14] simulated two and three-dimensional modeling of temperature flow fields in test cell used for steady natural convection experiments in liquid gallium. Three different three-dimensional numerical models are compared to each other and to that of an experimental radioscopic visualization. The temperature contours of three-dimensional numerical model were in good agreement with the experimental visualization. Tagawa et al. [15] experimentally measured the heat transfer rate of natural convection in liquid gallium in a cubical enclosure under an external magnetic field applied horizontally and parallel to the vertical heated wall and the opposing cooled wall of the enclosure. Experiments were conducted in the range of modified Rayleigh number from 1.85×10^6 to 4.76×10^6 and of Hartmann number from 0 to 573. The average Nusselt number was measured and found to increase when a moderate magnetic field was applied but to decrease under a stronger magnetic field. Yamanaka et al. [2] reported an experimental investigation of the average rate of heat transfer as well as the oscillatory span-widths of the Nusselt number and the Rayleigh number in a layer of liquid gallium. These quantities were determined by measuring the instantaneous temperature difference