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Free surface flow and heat transfer characteristics of liquid metal Galinstan at low flow velocity

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ABSTRACT

An effective method of obtaining a stable free surface flow with liquid metals is very important in terms of ensuring reliability of nuclear fusion devices. In this work, a miniature experimental apparatus was built and the characteristics of liquid-metal free surface flow and laminar convective heat transfer on different surface structures were experimentally investigated. The results show that, within a certain velocity range, Galinstan can flow in the form of an even liquid film on an acid-pickled stainless-steel surface. As the Galinstan flow rate increases, the convective heat transfer coefficient increases. Finally, a heat transfer correlation of free surface flow was proposed for the liquid-metal Galinstan.

1. Introduction

In nuclear fusion devices, limiter-divertors are employed as vital systems to separate high-temperature plasma from the vacuum chamber in Tokamaks, which is considered as the most promising type of magnetic confinement fusion reactor. Hence, investigations of liquid-metal limiter-divertors have been ongoing [1–4]. However, numerous scientific and technical problems still need to be solved, such as the method of obtaining steady-state liquid-metal free-surface flow, the magnetohydrodynamics (MHD) mechanism of liquid-metal free-surface flow, and the improvement of the heat transfer performance of liquid metal.

There are three flow patterns in liquid-metal free-surface flow, namely, film flow, jet, and liquid curtain [5]. Jet forms when liquid metal is pushed out from a nozzle, which requires a sufficient range of jet, constant fluid, and no deformation. Liquid curtain, which is considered to be a potential candidate of the future limiter-divertor, forms like the rain. The advantage of curtain flow is that the liquid metal is not continuous, and the electric current through the whole flow field will not be induced, thus, the MHD effect can be reduced consequently. Film flow, which is formed when liquid metal flows on a solid surface in form of a layer of liquid film, is considered as the only flow pattern that is applicable to the first wall of a fusion reactor, as well as the limiter-divertor system [6]. Nevertheless, up to now there is no efficient and safe method that can control the MHD effect [7]. Xu et al. [8] illustrated three types of flow characterizing the MHD effect of liquid-metal free-surface flow; namely laminar flow (jet-film flow), stream flow, and turbulent flow. Among these, laminar flow is regarded as the optimal free-surface pattern of liquid metal in a limiter-divertor system.

Lithium or lithium-lead alloy is the most promising liquid metal in nuclear fusion devices. However, their active chemical properties cause insecurity for conducting experiments. Therefore, liquid metal sodium has been studied extensively [9–11]. Zhang et al. [12] investigated the turbulent heat transfer performance of sodium in a loop pipe experimentally; the calculation formulae of the thermal entrance length and the Nusselt number of both the entrance region and the fully developed flow region were given, and the experimental values agreed well with the theoretical ones. The single-phase flow heat transfer characteristics of sodium in an annular channel were studied by Qiu et al. [13], who classified the single-phase flow into laminar flow, transition flow, and turbulent flow according to the experimental data; in addition, the fitted calculation expressions for the frictional coefficient and corresponding heat transfer relation under different flow states were obtained.

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Nomenclature

A	thermal contact area (m^2)
C_p	specific heat capacity [J/(kg °C)]
D	diameter (m)
G	volumetric flow rate (m^3/s)
H	height (m)
h	convective heat transfer coefficient [W/m^2 °C]
k	thermal conductivity [W/(m °C)]
L	characteristic length (m)
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Q	heat transfer rate (W)
Re	Reynolds number
R_a	averaged roughness (μm)
S	cross-sectional area (m^2)
T	temperature (°C)
T_s	wall temperature of sample substrate (°C)
u	flow velocity (m/s)

Greek letters

δ	thickness (m)
θ	contact angle (°)
μ	dynamic viscosity (Pa s)
ρ	mass density (kg/m^3)

Subscripts

1	inlet
2	outlet
l	liquid metal
w	cooling water
ss	stainless steel

In this work, experimental investigations on free surface flow and heat transfer characteristics of liquid Galinstan (whose physical properties are close to lithium) are carried out, which were seldom reported before. This paper will focus on the free surface laminar flow of liquid Galinstan at low Reynolds number, and meanwhile investigate its heat transfer potential in order to provide a reference for further study in limiter-divertors.

2. Experimental setup

For the purpose of investigating the free surface flow and heat transfer of Galinstan, a miniature experimental apparatus was set up, as shown in Fig. 1. The apparatus is comprised of a main loop and an auxiliary loop, and it is worth noting that the auxiliary loop was employed to provide cooling for the main loop.

The storage tank in the main loop was used for storage of the Galinstan, which is able to provide a continuous working medium for the loop. The test section is a cubic cavity made of stainless steel, as shown in Fig. 2. The overall size of the container is $150 \times 130 \times 150\ mm^3$, while the thickness of the wall is 5 mm. In addition, three perspective windows are on the upper, left, and right sides of the container (not shown in Fig. 1) in order to make it convenient for a high-speed camera to record the flow process of the liquid metal. The perspective windows, made of transparent PC board material, were fixed on the container by bolts and sealed by silicone adhesive. The upper cover plate of the test section can be disassembled; thus, different surface structures can be studied via disassembling the plate and replacing the structures.

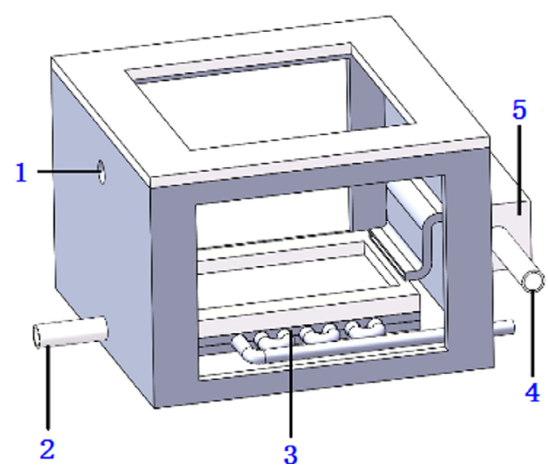

Fig. 2. Schematic of the test section: 1 vacuum-argon system; 2 temperature monitoring point of outgoing liquid metal; 3 test sample; 4 temperature monitoring point of incoming liquid metal; 5 buffer tank for liquid metal.

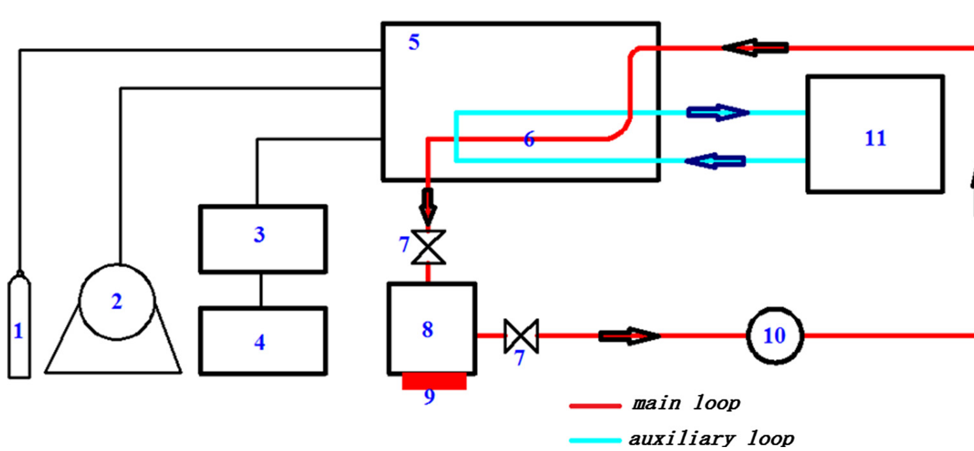

Fig. 1. Schematic of experimental system: 1 argon; 2 vacuum pump; 3 Agilent data-acquisition instrument; 4 computer; 5 test section; 6 test sample; 7 valve; 8 storage tank; 9 copper heating block; 10 peristaltic pump; 11 thermostatic water tank.