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Thermophysical properties of the liquid Ga–Sn–Zn eutectic alloy

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ABSTRACT

Higher demand and increased working temperatures in the energy production sector have prompted work on the development of new, more efficient and higher performance cooling for liquid metals. However, a lack of understanding of the thermophysical properties of the materials involved has limited the potential applications of such materials. This study presents the results of the temperature dependency of density, surface tension, viscosity, electrical conductivity, thermoelectric power and thermal conductivity for eutectic Ga–Sn–Zn. The conducted measurements show higher melting temperature and surface tension, and lower thermal expansion coefficient, density, viscosity, electrical conductivity and thermal conductivity of eutectic Ga–Sn–Zn compared to eutectic Ga–In–Sn.

1. Introduction

Demand for electrical energy has increased dramatically, and carbon remains the main source of such energy today. However, in order to stabilise the climate and reduce air pollution there is a need to expand focus on green and nuclear energy [1,2]. This is turn means the need for new cooling management systems to meet the requirements associated with the conversion of such energy. Heat transfer of internal energy within single or multiple bodies is achieved in three different ways: conduction, convection and radiation. In fluids, this energy is the kinetic energy of atoms and molecules, while in solids it is the vibration energy of atoms and the motion of free electrons. Heat convection is described as the movement of a liquid mass, rising from the heat source. A new approach to cooling proposes the use of the metal alloys characterised by high heat capacity and thermal conductivity compared to water. The application of liquid metal as a coolant in the nuclear power industry (the new generation Liquid Metal Fast Breeder Reactor (LMFBR) [3,4]) and in renewable energy sources (such as concentrated solar power (CSP) [5,6], electronics devices [7] and Li-ion batteries [8–10]), increases the efficiency and performance of such devices. Furthermore, there are designs for a new cooling management system using electromagnetic pumps (EMP), which further extends the potential applications of liquid metal cooling systems [9]. The EMP system exhibits reliable performance, and it is easy to control and manipulate the flow direction, which further increases efficiency compared to cooling by water. The biggest disadvantages of using liquid metal as a cooling system are cost and weight (the density of liquid metal is more than six times higher than that of water). However, liquid metals have the advantage of excellent heat extraction and spreading capability, which leads to more effective work and a reduction in the coolant charge [9]. The small modular reactor (SMR) [11] has attracted particular attention in recent years due to its outstanding technical, economic and safety characteristics. Lead or lead-bismuth eutectic (LBE) [12] fast-cooled reactor (LFR) [13] technology is very promising for closing the nuclear fuel cycle. As one of the reactor types emphasised in the Gen-IV initiative, LFR should display enhanced safety performance compared to reactors currently in operation. The passive cooling small modular LFR is considered among the potential candidates for developing the commercial application of LFR. It is possible that a small, safe SMR nuclear reactor could be used as a power source for the new EmDrive thruster [14], the development of which is increasing demand for electrical power. To power the super-efficient systems, and to ensure stable operation, appropriate cooling and heat dissipation systems must be developed. The EmDrive, if equipped with a portable nuclear reactor with a capacity of 1–100 MW [14], will enable speeds of up to 9.4% of the

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speed of light to be reached. Thus, the development of liquid metal cooling in modern technologies for electronics and ion-batteries is connected with the introduction of super-processors [8,15]. The performance and stability of microprocessors is closely linked to the discharge of heat from the system by coolers in which liquid metals with much higher thermal conductivity can be applied. The latest applications of low-melting alloys change and manipulate the shape of the liquid alloy. This is possible when an electric charge is applied to a gallium alloy in water, as at room temperature the alloy is a liquid [16]. The microfluid applications which could control the movement of liquid [17] in microelectromechanical systems have great potential as switches, pumps, valves, sensors, and electrodes [18–21].

This work is on the development of heat transfer fluids to extend the working temperature range and reduce the melting point (to reduce heat tracing requirements) simultaneously with a high boiling temperature to allow efficient thermodynamic cycles. The coolant should also be characterised by high thermal conductivity (λ), which is desired for efficient heat transfer, low viscosity (η), which is beneficial for pressure drop and pumping power, and a high heat capacity (c_p), which would allow for direct thermal storage and improve safety (toxicity) and corrosion behaviour [6]. The liquid metals which are most frequently used in these applications are tin (Sn), gallium (Ga), lithium (Li), sodium (Na) and lead-bismuth (PbBi). Na, Bi and BiPb are already used in nuclear power engineering. Gallium can be used as a coolant in nuclear reactors, to extend the life of electronic devices and their resistance to damage, and even to cool standard processors. The physical and thermal properties of Ga make it ideal for removing heat from powerful sources such as, for example, today's CPUs [7]. The high boiling point of Ga, reaching more than (2510 K) [6], allows for cooling of high-performance equipment without phase changes. Ga is non-flammable, non-toxic and environmentally friendly. However, the excessive costs of Ga, similar to In [6], mean it can be used in special high technology of cooling systems. Its excellent thermal conductivity makes it a great recipient of heat energy and allows the swift return of collected energy in the heat exchange. Its electrical conductivity allows the use of a system with electromagnetic pumps.

The proposed eutectic Ga–Sn–Zn alloy was studied using the steady-state concentric cylinder method to obtain values for thermal conductivity, the four-point method for electrical conductivity, thermoelectric power measurements, calorimetry to assess the melting point, thermal mechanical analysis to obtain the thermal expansion, and the discharge crucible method (DC) to measure the density, surface tension and viscosity of the samples.

2. Experimental

2.1. Material

The alloys were prepared using pure Ga (99.99999% PPM Pure Metals), Sn and Zn (99.999% Alfa Aeaser) in a glovebox under a protective atmosphere of high purity argon (99.9999% Air Products), with water vapour, nitrogen and oxygen concentrations lower than 0.1 ppm to avoid the oxidation of liquid alloys. Such a low value of H_2O and O_2 was obtained by the application of a high temperature gas purifier working with Ti shavings at 850 °C [22]. The eutectic Ga–Sn–Zn was melted in a graphite crucible in an electrical furnace. The chemical composition of the studied eutectic Ga–Sn–Zn alloy, 90.15 of Ga, 6.64 of Sn and 3.21 of Zn (at. %) corresponding to 86.3, 10.8 and 2.9 (wt %), respectively, was chosen according to the phase diagram and DTA measurements [23]. The experimental results of density, surface tension, viscosity electrical conductivity, thermal conductivity and thermoelectric power are collected in Tables S1–S6.

2.2. Methods

2.2.1. Calorimetry

The calorimetry study was performed with a high precision differential scanning calorimeter, type Q1000 (TA Instrument). Measurements were conducted in a controlled inert gas atmosphere: helium, 20 ml/min with a temperature range of 223–343 K and a heating rate of 1 K/min. Thermal expansion was studied in a TMA Netzsch F1 thermal mechanical analyser with a temperature range of 223–343 K at a heating rate 1 K/min, and, in order to determine the thermal linear coefficient (CTE), in the range of 298–823 K at a heating rate 5 K/min.

2.2.2. Discharge crucible method

Density, surface tension and viscosity were studied using equipment based on the discharge crucible method presented in Fig. 1.

The method is based on the dependency of mass change over time, and the use of numerical solutions [24,25] to analyse the results. The equipment was calibrated using pure metals and alloys [24–27]. Determining the density, surface tension and viscosity was based on the relationship between the volumetric flow rate of liquid Q exiting the crucible through the orifice of fixed radius r_0. The head of the liquid, is calculated using equation (1):

$$h = \frac{1}{2g}\left[\frac{Q}{\left(a_4\left(\frac{2\rho Q}{\pi r_0 \eta}\right)^3 + a_3\left(\frac{2\rho Q}{\pi r_0 \eta}\right)^2 + a_2\left(\frac{2\rho Q}{\pi r_0 \eta}\right) + a_1\right)\pi r_0^2}\right] + \frac{\gamma}{\rho g r_0} \tag{1}$$

where: ρ is the density of liquid (kg/m^3), g is the gravitational acceleration (m/s^2), r_0 is the orifice radius in the bottom of crucible (m), Q is the free flow rate (m^3/s), η and γ are the viscosity (mPa·s) and surface tension (mN/m), respectively, and a_1, a_2, a_3 and a_4 are constants in the polynomial describing the dependency of C_d versus *Re* [24].

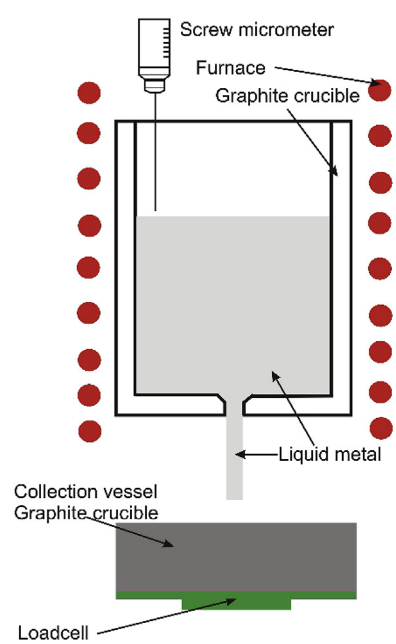

Fig. 1. Equipment for simultaneous measurement of density, surface tension and viscosity.