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Evaluation of thermal conductivity for liquid lead lithium alloys at various Li concentrations based on measurement and evaluation of density, thermal diffusivity and specific heat of alloys

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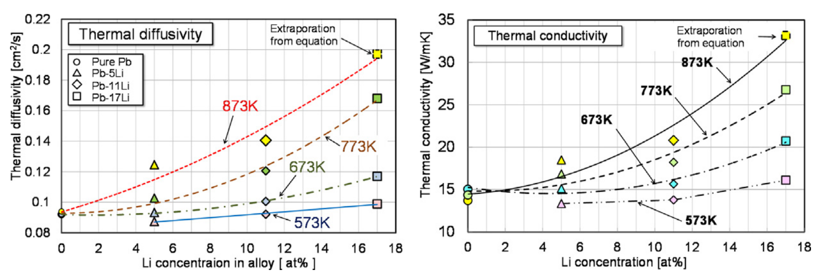
HIGHLIGHTS

- The densities and specific heats of liquid Pb–Li alloys are evaluated based on the previous studies, and mathematically expressed in the equations with the functions of temperature and Li concentration.
- The thermal diffusivities of liquid Pb–Li alloys (i.e., Pb–5Li, Pb–11Li and Pb–17Li) are obtained by laser flash method, and mathematically expressed in the equations with the functions of temperature and Li concentration.
- The thermal conductivities of liquid Pb–Li alloys were evaluated and mathematically expressed in the equations with the functions of temperature and Li concentration.

GRAPHICAL ABSTRACT

Thermal diffusivities and thermal conductivities of liquid Pb–Li alloys (Pb–5Li, Pb–11Li and Pb–17Li).



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ABSTRACT

The thermophysical properties of lead lithium alloy (Pb–Li) are essential for the design of liquid Pb–Li blanket system. The purpose of the present study is to make clear the density, the thermal diffusivity and the heat conductivity of the alloys as functions of temperature and Li concentration. The densities of the solid alloys were measured by means of the Archimedean method. The densities of the alloys at 300 K as a function of Li concentration ($0\,\text{at\%} < \chi_{Li} < 28\,\text{at\%}$) were obtained in the equation as $\rho_{(300\,K)}\,[\text{g/cm}^3] = -6.02 \times 10^{-2} \times \chi_{Li} + 11.3$. The density of the liquid alloys was formulated as functions of temperature and Li concentration ($0\,\text{at\%} < \chi_{Li} < 30\,\text{at\%}$), and expressed in the equation as $\rho\,[\text{g/cm}^3] = (9.00 \times 10^{-6} \times T - 7.01 \times 10^{-2}) \times \chi_{Li} + 11.4 - 1.19 \times 10^{-3} T$. The thermal diffusivity of Pb, Pb–5Li, Pb–11Li and Pb–17Li were measured by means of laser flash method. The thermal diffusivity of Pb–17Li was obtained in the equation as $\alpha_{Pb-17Li}\,[\text{cm}^2/\text{s}] = 3.46 \times 10^{-4} T + 1.05 \times 10^{-1}$ for the temperature range between 573 K and 773 K. The thermal conductivity of the Pb–17Li at the temperature of 773 K was newly obtained and expressed in the equation as $\lambda\,[\text{W/mK}] = 4.47 \times 10^{-2} \chi_{Li}{}^2 - 0.08 \chi_{Li} + 14.9$. The dependence of Li concentration on the thermal diffusivities of the alloys was larger at higher temperature. The temperature dependence of the thermal conductivities of the alloys was larger when the Li concentration in the alloys was higher.

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1. Introduction

Liquid lead lithium alloy (Pb–Li) is one of the candidates of the tritium breeders of fusion reactors. The thermophysical properties of the alloy, such as thermal diffusivity, specific heat, viscosity and density, are essential for the blanket design.

The thermophysical properties of Pb–17Li are summarized in Ref. [1]. The vapor pressures and the boiling points of the alloys are reported in Ref. [2]. The thermal diffusivity and conductivity of Pb–17Li was reported in Ref. [3]. The densities of alloys at the Li concentration between 20 and 90% were measured in the previous study [4]. The density data at the Li concentration less than 20 at% is still limited, though that at the eutectic composition was studied [3,5]. The density data of the alloys in a solid state are important for their quality evaluation before the installation of the alloy into the blanket. The specific heat of the alloy was studied in the previous study [4]. However, the available data for their thermophysical properties are quite limited, though these are essential to evaluate the heat transfer characteristics of the liquid blanket system.

It is known that lithium (Li) can be depleted from the alloys by their oxidation. Then, the alloy's composition is changed as reported in the previous study [6]. The depletion of Li from the alloy during the reactor operation for a long term is important issue, since the neutronic and thermophysical performances of the alloy must be deteriorated by the decrease of Li concentration [7]. The thermophysical properties as the functions of Li concentration and temperature must be made clear.

The purpose of the present study is to make clear the density, the thermal diffusivity and the thermal conductivity of the Pb–Li alloys having Li concentrations in the range between 0 and 30 at%. The density data of the alloys in a solid state were obtained by means of the Archimedean method. The density data as the functions of temperature and Li concentration were expressed in the equation based on the present and previous studies. The thermal diffusivity of the alloys was measured by laser flash method, and the experimental data was expressed in the equation. Then, the thermal conductivity of the alloys as the function of temperature and Li concentration was evaluated.

2. Experimental conditions

2.1. Fabrication of lead lithium alloy [6]

The Pb–Li alloys having various Li concentrations were fabricated using small metal grains of Pb and Li at the temperature around 723 K. The compositions of the alloys were adjusted by the mixture of the alloys having different Li concentrations. The Li concentrations of the alloys were determined by the measurement of their melting points and the chemical analysis with ICP-AES. The samples used in the current work are summarized in Table 1.

2.2. Experimental conditions

2.2.1. Measurement of density

The cylindrical type specimens for the density measurement were prepared by the casting. The size of the specimen was Φ17.6 mm × 28 mm. The densities of the alloys were measured by means of Archimedean method. Though the chemical activity of Li in Pb–Li alloy is low [2], the alloy reacts with water very slightly. Therefore, the specimen made of Pb–Li was immersed in acetone, which does not react with the alloy, for the measurement at room temperature to suppress the chemical reactions. It is difficult to measure the density at the temperature higher than 330 K by using acetone, since the measurement is affected by the boiling of acetone due to its low boiling point as 330 K. Then, glycerol was selected as the chemically inactive liquid for the density measurement at the temperature higher than 330 K, since its boiling point is 563 K.

The density was evaluated according to the equation;

$$\rho_{\text{alloy}} = \frac{m_{\text{air}}}{m_{\text{air}} - m_{\text{liquid}}}(\rho_{\text{liquid}} - \rho_{\text{air}}) - \rho_{\text{air}} \tag{1}$$

where m_{liquid} [g] is the mass measured in the liquid, m_{air} [g] is the mass measured in the air atmosphere, ρ_{liquid} [g/cm^3] is the density of the liquid and ρ_{air} [g/cm^3] is the density of air.

2.2.2. Measurement of thermal diffusivity

The thermal diffusivity was measured by means of laser flash method using ULVAC TC-9000. The laser flash technique has been used to measure the thermal diffusivity of liquid metals [8] and molten salts [9]. The composition change of Pb–Li by its oxidation at high temperature during the measurement can be suppressed, since the data of thermal diffusivity can be acquired in a short time by this technique. The disk type samples having the diameter less than 9 mm and the thickness of 1 mm were prepared as presented in Table 1. The alloys of Pb–5Li, Pb–11Li and Pb–17Li were selected as the test materials for the measurement of thermal diffusivity to understand the relationship between the Li concentration and their thermophysical properties in a well-balanced manner. The sample was placed in the sample holder made of graphite as shown in Fig. 1. The sample holder was installed in the chamber, and heated by a heater of the chamber. The test temperature was measured by the thermocouple, which was installed on the surface of the sample holder. The neodymium (Nd) glass laser was irradiated to the top part of the capsule, and the temperature change of the bottom plane of the sample was measured by the infrared detector. The wave length of the laser is 1.07 μm and the output for one pulse is 10 J. The pulse duration is 0.49 ms. The measurement tests were performed under the vacuum condition of 1 Pa.

The upper plane of the thin film (i.e., the sample of liquid alloy) is heated by the laser irradiation in the measurement procedure. Then, the temperature distribution is formed as the temperature of the upper plane is higher than that of the bottom plane. The Rayleigh-Bénard convection in this thin film is not caused due to this temperature distribution. Therefore, the effect of the thermal

Table 1
Test samples for measurement of density and thermal diffusivity of Pb–Li alloy.

Pb–Li alloy	Density measurement of alloys in a solid state (mass [g])	Thermal diffusivity measurement of solid and liquid alloys (thickness [mm])
Pb (purity is 99.9% in Ref. [6])	Cylindrical sample (54.46)	Disk type sample (1.06)
Pb–5Li (fabricated in test ID 16 in Ref. [6])	–	Disk type sample (1.086)
Pb–11Li (fabricate in same way to test ID 2 and 3 in Ref. [6])	Cylindrical sample (48.87)	Disk type sample (1.06)
Pb–15Li	Cylindrical sample (45.18)	–
Pb–17Li (fabricated in test IDs 17 and 18 in Ref. [6])	Cylindrical sample (52.37)	Disk type sample (1.084)
Pb–19Li	Cylindrical sample (48.06)	–
Pb–25Li (fabricate in same way to test ID 7 in Ref. [6])	Cylindrical sample (49.00)	–
Pb–28Li (fabricated in test ID 9 in Ref. [6])	Cylindrical sample (46.59)	–

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