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Study on hydrogen isotope behavior in Pb-Li forced convection flow with permeable wall

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HIGHLIGHTS

- Transient- and steady-state hydrogen permeation from Li-Pb forced convection flow through permeable tube to outside Ar purge gas was investigated at 600 °C.
- It was found that the overall permeation rates were limited by diffusion in the Li-Pb boundary layer developed from the flow inlet.
- The effect of the boundary layer was correlated in terms of mass transfer coefficient. The values of mass transfer coefficients at 600 °C were compared with those of 400 °C and 500 °C obtained beforehand.

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ABSTRACT

Transient- and steady-state hydrogen permeation from Li-Pb forced convection flow in a permeable tube to outside Ar purge gas was investigated between 400–600 °C. The values of the steady-state permeation rate increased with the increase of the Li-Pb flow rate. It was found that the overall permeation rates were limited by diffusion in a Li-Pb boundary layer developed from flow inlet. The effect of the boundary layer was correlated in terms of the mass-transfer coefficient. The values of the mass-transfer coefficient at 600 °C were compared with those of 400 °C and 500 °C obtained beforehand. Judged from these data of mass-transfer coefficients, it can be predicted that the effect of boundary layer varies with the increase of Li-Pb flow rate at different temperature conditions.

1. Introduction

D–T fusion reactors are expected to become a system to provide the main electricity in the future. Blanket is indispensable equipment of fusion reactors, and it has to play several important roles for that. The first role is to convert neutron kinetic energy through heat to finally electricity. Furthermore, breeding tritium fuel is an essential role for fuel self-sufficiency. Several liquid or ceramic blanket concepts have been proposed using candidate materials. Especially, a lithium-lead eutectic alloy (Li-Pb) is considered one of the most prospective candidates for a liquid blanket material in a D–T fusion reactor. Li-Pb can work as a tritium breeder or even as a dual coolant material in a fusion reactor. Therefore, Li-Pb can be adopted in several blanket concepts. For examples, the He-cooled lead lithium (HCLL) and the dual-coolant lead lithium (DCLL) blanket are proposed as the conceptual design [1,2]. This material is also supposed to be used as a liquid wall material in KOYO-fast laser fusion reactor in Japan [3]. Since Li-Pb is a highly promising material as shown above, detailed data on transport properties of tritium under static or fluidized Li-Pb conditions are indispensable.

Diffusivity and solubility of hydrogen isotopes in Li-Pb have been determined so far [4–6]. Isotope effects among hydrogen isotopes and interactions between hydrogen isotopes and Li-Pb have been already revealed previously [7]. Even though reasonable experimental results were determined, there are some points to remain to be unresolved. Understanding effects of Li-Pb fluidized states on the overall tritium permeation is one of them. Li-Pb breeder in fusion blankets is supposed to be used under fluidized states, and simultaneous transfer of heat and tritium occurs in a blanket loop. Thus, it is important to know how quantitatively Li-Pb flowing states affect the tritium transfer behavior.

In our previous study [8], H_2 permeation behavior under Li-Pb forced convection flow at 500 °C and 400 °C was investigated. However, Li-Pb is supposed to be used in a wider range of temperature conditions to achieve high thermal efficiency. Thus, it is necessary

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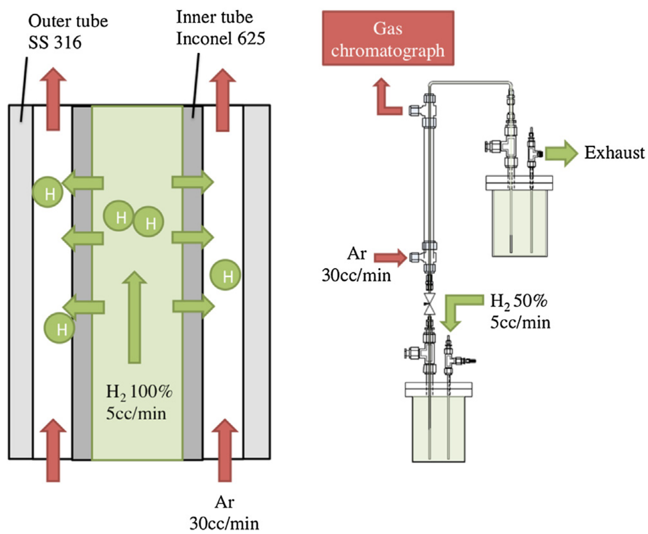

Fig. 1. Schematic diagrams of flow arrangement and dual cylindrical tubes.

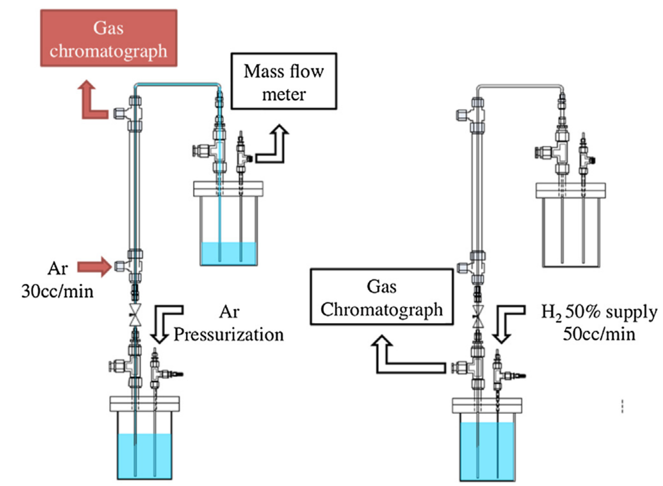

Fig. 2. A schematic diagram of the forced convection Li-Pb flow test. Right part shows the H_2 supply process, and left part does the Li-Pb flowing process.

to confirm H_2 permeation behavior at a wider range of temperature conditions.

The main purpose of this paper is to figure out how forced convection states of Li-Pb affect the hydrogen transport behavior at several temperature conditions. Experiments of hydrogen transfer through forced-convention Li-Pb flow in a dual cylindrical tube at 600 °C are performed. Transient- or steady-state hydrogen permeation from Li-Pb forced convection flow through a permeable wall to outside purge gas is investigated. Data at 500 °C and 400 °C were already presented in the previous research [8]. Data at 600 °C are compared with those at 500 °C and 400 °C in order to figure out the influence of temperature condition on H_2 permeation rate under the Li-Pb fluidized state.

2. Experimental

The experimental apparatus used in this study is the same as one presented in our previous paper [8]. The experimental apparatus consists of dual cylindrical tubes and two Li-Pb storage tanks made of SS304 that have thickness of 3 mm. H_2 is recovered through this dual cylindrical tubes. The length of the dual cylindrical tubes for the Li-Pb forced convection flow is 80 cm. The inner tube is 6.35 mm in diameter, 1.0 mm in thickness and made of Inconel-625, which has a composition ratio of $x_{Ni} = 0.61$, $x_{Cr} = 0.22$, $x_{Mo} = 0.09$, $x_{Fe} = 0.05$ and $x_{Nb+Ta} = 0.03$ in atomic molar fraction. The outer tube is made of SS316 and has the dimension of 9.53 mm in diameter and 1.0 mm in thickness. The reason why Inconel-625 tubing is selected as the Li-Pb facing material is not because Inconel is a candidate material for the future blanket but because the alloy is available one that has properties of high H permeability and high corrosion resistance. Two experiments of blank flow test under Ar-H_2 gas mixture and forced convection Li-Pb flow test are conducted using this apparatus. Experimental conditions of temperature are selected as the target one of DCLL DEMO design [1,2]. The hydrogen concentration in Li-Pb is selected so as to that the H solution in Li-Pb obeys the Sieverts' law, which is also applied to an actual blanket loop.

2.1. Blank experiment

Fig. 1 shows schematic diagrams of the flow arrangement and dual cylindrical tubes. The main purpose of this blank test is to confirm whether or not the experiment apparatus set up newly in our laboratory works well. In this test, H_2 100% gas of the molar flow rate 3.71×10^{-6} mol/s is continuously supplied to the inner flow section. Consequently, the inner tube is filled with pure H_2 gas at 1.0133×10^5 Pa. Hydrogen diffuses inside the inner tube and permeates through tube wall to the outside Ar purge. Hydrogen in the outer tube is purged out by Ar of 2.23×10^{-5} mol/s, and then the H_2 concentration in the Ar + H_2 mixture is measured by gas chromatography.

2.2. Forced Li-Pb flow experiment

Fig. 2 shows a schematic diagram of the forced convection Li-Pb flow test. Several steps are performed in the forced convection Li-Pb flow experiment. The first step is to absorb H atom into Li-Pb in a bottom storage tank as shown in the right part of Fig. 2. H_2 is charged in Li-Pb by bubbling Ar-H_2 mixture gas. The H_2 molar fraction is 0.5, and the flow rate is 3.71×10^{-5} mol/s. The concentration of H_2 gas effluent from the Li-Pb tank is measured by gas chromatography. This H_2 charge process is continued till Li-Pb becomes saturated with the supplied H_2 concentration. Next, Li-Pb is pressurized by pure Ar gas as shown in the left part of Fig. 2. When Ar gas is supplied to the bottom tank with regulated pressure and flow rate, it pushes up Li-Pb into the upper tank with an almost constant flow rate. The Ar gas present in the upper tank originally is replaced by flowing Li-Pb. The flow rate of Ar gas effluent from upper tank is measured, and it is considered to be equal to the flow rate of Li-Pb. Finally, the H_2 permeation rate is determined by the H_2 concentration in purge gas inside the outer cylinder tube. H in Li-Pb diffuses inside and permeates through inner tube wall. H_2 reaches the space between the middle and outer tubes. Ar gas of 2.23×10^{-5} mol/s is also supplied to purge out and the H_2 concentration is determined by gas chromatography.

3. Analysis

3.1. Blank experiment

The H permeability through a metallic wall is determined from steady-state H permeation rates of the blank experiment. Diffusion in the metallic wall is supposed to be the rate-determining step of the overall permeation process in this system. Furthermore, it is well known that hydrogen in a metal is dissolved as a form of atom, and its dissolution follows the Sieverts' law. Thus, the steady-state H_2 permeation rate of the blank experiment is expressed as

$$j_{H,S} = \frac{P_{H,S}}{L}\left(\sqrt{P_{H_2,LiPb}} - \sqrt{P_{H_2,Ar}}\right) \quad (1)$$

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