DEUTERIUM TRANSPORT PREDICTION IN OSCILLATING LIQUID Pb-17Li DROPLET

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The feasibility of deuterium mass transport prediction from falling droplets of Pb-17Li was verified. This prediction is one of key techniques of the engineering design of tritium extraction device for the fusion reactor. The mass-transfer-coefficient, deduced on the surface-stretch-model was applied. As the experimental results, deuterium mass transport in the falling droplets from four different size nozzles, at four temperature conditions between 375 ºC and 450 ºC, performed by the authors, were compared. Resultant Sherwood number was between 494 and 598, and explained the experimental result of the two orders of magnitudes differences with the reported diffusion in static condition. Though, the ratio of theory and experiment still remained between 1.8 and 2.3. Simple boundary condition, not considering the number of oscillation, wide range of reported diffusivity value are considered to be main reasons of the deviation. The analysis model including these factors is to improve prediction accuracy. This result is expected to contribute to a preliminary design of a tritium extraction device.

I. INTRODUCTION

We have proposed a conceptual high temperature liquid Pb-17Li blanket and a related process for the recovery of tritium with a vacuum-sieve-tray (VST). This device aims to extract dissolved tritium, from liquid Pb-17Li droplets, while the droplets are falling in vacuum.

The authors reported that the mass transport of deuterium from Pb17Li droplets, while falling in vacuum, was approximately two orders of magnitudes faster than the estimation from the previous reports.[1-3] Through the use of high speed movies, cyclic deformation of the spherical shape of the droplets was observed, which suggested the possible cause of the faster observed mass transfer.

Due to the unsteady-state transfer process of a falling droplet, many sophisticated studies of mass transfer from droplets have been performed mainly by numerical calculation.[4] On the other hand, for the proto-type design engineering of tritium extraction device, rather simple analytical Sherwood number and mass transfer coefficient of hydrogen isotopes from falling liquid Pb-17Li droplet in a short period, was requested but so far not established.

This paper intends to validate the availability of simple criteria for the mass transfer of deuterium extracted from falling droplets of liquid Pb-17Li in a vacuum.

II. MASS TRANSFER COEFFICIENT

II.A. Analysis of the Droplet Oscillation

The frequency of cyclic deformation of a falling droplet was observed to be approximately 200 [Hz] in case of emitted from 0.6mm diameter nozzle by the previous report.[1]

Bulk properties of liquid Pb-17Li were examined by comparing the non-dimensional parameters that characterize the behavior of the falling droplet. As shown in TABLE I, liquid Pb-17Li at temperatures between 400 °C and 500 °C is categorized as a typical Weber number dominated material, i.e., surface tension dominates the physical behavior of its motion. It is roughly one order greater than the gravity effects represented by the Froude number, and two orders greater than the viscosity effects represented by the Reynolds number. The natural frequency of a small liquid droplet under surface tension domain, is described by the following equation when surrounded by an infinite mass of another liquid

$$f_d = \frac{1}{2\pi}\sqrt{\frac{n\ \ n+1\ \ \ n-1\ \ \ n+2\ \ \sigma}{a^3\left[\ n+1\ \ \rho_d + n\rho_c\ \right]}} \qquad (1)$$

where **n** is a solid harmonics of $\mathbf{n}^{th}$ degree and **n**=2 is the basic mode of oscillation.[5]

The calculated frequency of an n=2 basic mode oscillation is f_d=227.1 [Hz], frequency of an n=3 mode oscillation is f_d=439.8 [Hz]. The modal deformation at n=2 is well known to have as an axisymmetric shape and a cyclic transition between spherical and vertically oblong and oblate, as schematically depicted in Fig. 1 (Ref.5).

Fig. 1. Simulation model of modal deformation of a droplet, oscillating at basic mode (n=2) of natural frequency. It shows an axisymmetric deformation.

II.B. Mass Transfer Analysis of an Oscillating Droplet

The mass transfer theory of oscillating droplets by analytical methods, were summarized by A. Kumar and S. Hartland (Ref. 6). As to the mass transfer coefficient of an oscillating droplet under dispersive mode, two methods were introduced. One is a surface-stretch model.[7,8] The other is the new-surface-element model.[9] Each method was based on the different hypothesis, but the deduced results were close to each other. In this study, by the observation of the droplet oscillation, the results of the surface-stretch model were used. The basic hypothesis is closer to the observed results.

By the works of Angelo et al., the mass transfer coefficient was described as

$$k_d = \sqrt{\frac{4D f_d \left(1+\varepsilon+\frac{3\varepsilon^2}{8}\right)}{\pi}} \qquad (2)\ (\text{Ref.7, 8})$$

Corresponding Sherwood number is described from the definition as

$$S_h = \frac{k_d d_d}{D} = \sqrt{\frac{4 f_d \ d_d^{\ 2}\left(1+\varepsilon+\frac{3\varepsilon^2}{8}\right)}{\pi D}} \qquad (3)$$

In this study, due to the droplets are falling in vacuum, the overall mass transfer coefficient is assumed same with mass transfer efficient of the droplet.

III. RESULTS AND DISCUSSION

III.A. A Comparison of the Sherwood Number with the Experimental Results

As shown in Fig. 2, the Sherwood number for oscillating droplets and the experimental results[1] are plotted in the same chart. The vertical axis shows the Sherwood number, and the horizontal axis shows the reciprocal the temperature. Experimental is performed under four different temperatures of 375 ºC, 400 ºC, 425 ºC and 450 ºC. A surface stretch ratio is assumed ε=0.1 in all four droplet size, due to the resolution limit of high-speed recordings, significant difference was not distinguished.

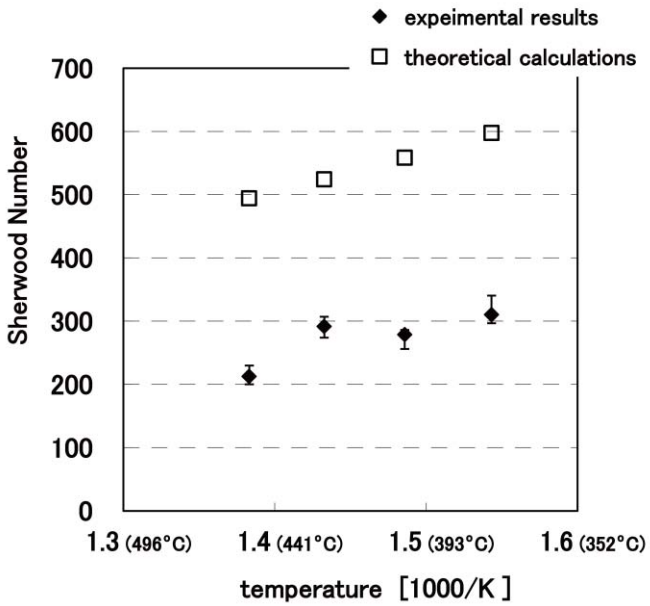

Fig. 2. Plots of theoretical Sherwood numbers compared with experimental results. Horizontal axis is reciprocal the temperature, vertical axis is Sherwood number.

As shown in Fig. 2, theoretically calculated Sherwood numbers and corresponding experimental results were plotted on the same chart. Theoretical Sherwood numbers were between 494 and 598. The experimental results were between 213 and 310. This result explained the two orders of magnitudes difference of the deuterium mass transport from falling droplets. Temperature dependency showed good accordance with each other. Though, the ratio of theory and experimental still remain between 1.8 and 2.3.

III.B. Discussion

The theoretical result showed 1.8 to 2.3 times higher than the experimental result. It is considered as follows.

a) The amount of solute in a droplet is finite. The concentration of the solute in a droplet must decrease by each emission, but it is not taken into account to deduce the equation. The corresponding boundary condition, $c = c_0|_{y=0,\,t>0}$ (Ref. 7, 8) which means the concentration on the stretched surface is always same with the beginning, does not reflect the true situation of a falling droplet in

vacuum. So theoretically deduced result dully shows higher value, and it is as shown in Fig. 2.

b) The number of deformation cycle within one droplet falling time, is not taken into account. Total amount of release must depend on the number of emission, but it is not considered. This also decreases the experimental result.

c) The diffusivity value reported by previous studies has larger deviation, possibly due to the difference of the measurement method.[2,3] This affects the calculation.

The other errors and uncertainty on the parameters such as viscosity due to the Li-Pb contents, or radius of the droplets can also be the reason for the discrepancy. They could also affect the result but it is presumed to be rather small compared with above three items.

IV. CONCLUSIONS

For the prediction of released amount of hydrogen isotopes from falling liquid Pb-17Li droplets in vacuum, the mass transfer coefficient by Angelo et al. (Ref. 8) was compared with the experimental results. The theoretical Sherwood number was between 494 and 598, and explained the two orders of magnitudes faster mass transport phenomenon. Though, the ratio of theory and experimental still remain between 1.8 and 2.3. To attain a better prediction, an analytical model which include more realistic boundary condition, the number of droplet oscillation while falling, or accurate diffusivity values will be required. However for the practical purpose, the agreement is in a reasonable level for this kind of very simple model, for understanding and taking into account the movement of liquid metal in fusion devices. Similar approach may be applicable for other liquid metal systems to be expected for fusion devices.

NOMENCLATURE

a	Radius of the droplet [m]
D	Diffusivity [m^2/s]
f_d	Natural frequency of droplet oscillation [1/s]
k_d	Mass transfer coefficient [m/s]
ε	Surface area deformation ratio [-]
ρ_d	Density of the droplet [Kg/m^3]
ρ_c	Density of surrounding medium [Kg/m^3]
σ	Surface tension [N/m]

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TABLE I. Non-dimensional parameter comparison of liquid Pb-17Li[4] Surface tension, represented by Weber number, dominates the behavior of the liquid Pb-17Li at temperature between 400 ºC and 500 ºC.

	Density	Dynamic viscosity	Kinematic viscosity	Surface tension	Temperature	Characteristic velocity	Characteristic length	Reynolds number	Froude number	Weber number
	ρ	μ	$\nu=\mu/\rho$	σ	T	U_{ch}	L_{ch}	Re	Fr	We
	Kg/m^3	Ns/m^2	m^2/s	N/m	°C	m/s	m	$U_{ch} L_{ch}/\nu$	$U_{ch}^2/g\ L_{ch}$	$\rho\ U_{ch}^2 L_{ch}/\sigma$
Pb-17Li	$9.7x10^3$	$1.5x10^{-3}$	$1.5x10^{-7}$	$4.5x10^{-1}$	400	3	$1.0x10^{-3}$	$2.0x10^4$	$9.2x10^2$	$1.9x10^2$
Pb-17Li	$9.6x10^3$	$1.2x10^{-3}$	$1.3x10^{-7}$	$4.4x10^{-1}$	500	3	$1.0x10^{-3}$	$2.3x10^4$	$9.2x10^2$	$2.0x10^2$