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Impact of the beam pressure on the free surface of the liquid lithium target of fusion neutron sources

Makoto M. Nakamura*[,a], Hiroo Kondo[a], Takuji Kanemura[b], Makoto Oyaidzu[a], Kentaro Ochiai[a], Hiromitsu Suzuki[a]

[a] Rokkasho Fusion Institute, National Institutes for Quantum and Radiological Science and Technology, Rokkasho, Aomori 039-3212, Japan
[b] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

Accelerator-driven fusion neutron sources, e.g. Advanced Fusion Neutron Source (A-FNS) and DEMO Oriented Neutron Source (IFMIF-DONES), are being designed, based on the achievements and lessons learnt from the IFMIF/EVEDA project. The purpose of the study is to analytically evaluate the deformation of the lithium free surface, potentially created by the intense beam injection. We have developed a two-dimensional (2-D) fluid model of the "beam-on" target of an IFMIF-type fusion neutron source by extending the phenomenological 2-D model of the Li target flow of the EVEDA Lithium Test Loop (ELTL). We have derived, from the newly developed model, a practical and analytical formula of the thickness of the "beam-on" target in the flow direction with accounting for the beam injection effect. We have also evaluated the thickness of the beam-on target of A-FNS as an example of application of the derived formula. The evaluation indicates that under the reference design conditions of the accelerator and beam-on Li target of A-FNS, the deformation of the free surface of the target by the beam injection is negligibly small. The analytical results presented here may be used for a benchmark of more complicated CFD simulation for the "beam-on" target design of IFMIF-type fusion neutron sources like A-FNS and IFMIF-DONES.

1. Introduction

A fusion neutron source producing energetic neutrons with the energy of $>$ 10 MeV is necessary for testing and validating fusion reactor materials. A straightforward approach of such material testing may be to build a volumetric, e.g. tokamak, DT fusion neutron source [1,2], but it will need to procure the large amount of tritium for machine commissioning and operation. Another approach is to simulate generation of the 14-MeV DT neutron by utilizing the accelerator-driven Li(d,nx) reactions, like International Fusion Materials Irradiation Facility (IFMIF) [3]. Now in Japan and European Union (EU), accelerator-driven, intense fusion neutron sources, named Advanced Fusion Neutron Source (A-FNS) [4–6] and DEMO-Oriented Neutron Source (IFMIF-DONES) [7], respectively, are being designed independently by effectively utilizing the outcomes obtained and lessons learned from the IFMIF/EVEDA project [8,9] and with aiming at early offering neutron irradiation data of fusion reactor materials to an engineering design of a fusion DEMO reactor.

In the designs of A-FNS and IFMIF-DONES, the target lithium (Li) is not solid, but liquid with the free surface, unlikely conventional accelerator-driven particle sources, in order to divert the intense beam power deposited to the target. Steady-state operation of the liquid Li target with the stable free surface has been engineeringly validated in the EVEDA Li Test Loop (ELTL) for the long duration of $>$ 1000 hours [10], which was conducted under the IFMIF/EVEDA project. Although the liquid Li target in the ELTL experiments was not exposed to the intense deuteron beam, the thermofluid behaviors of the target with the beam injection, so-called "beam-on" target, was analyzed by numerical fluid simulations for the IFMIF design [11,12].

The previous numerical simulations for the IFMIF "beam-on" target design, however, assumed that the shape of the free surface of the Li target, into which the beam deposits the energy and momentum, was fixed as a simulation condition. In general, if a force is applied to a fluid object, its free surface is deformed. In fact, the deformation of the liquid Li by the centrifugal force, caused by the concave target backplate, has been observed in the ELTL experiments [13]. Kanemura et al. [13] reported that the centrifugal force, the vector of which was vertical to the direction of the main Li flow, leads to the increase in the thickness of the Li target (see Fig. 5 in Ref. [13]). Knaster [14] preliminary estimated the contribution of the beam injection to the pressure of the

* Corresponding author.
E-mail address: nakamura.makoto@qst.go.jp (M.M. Nakamura).

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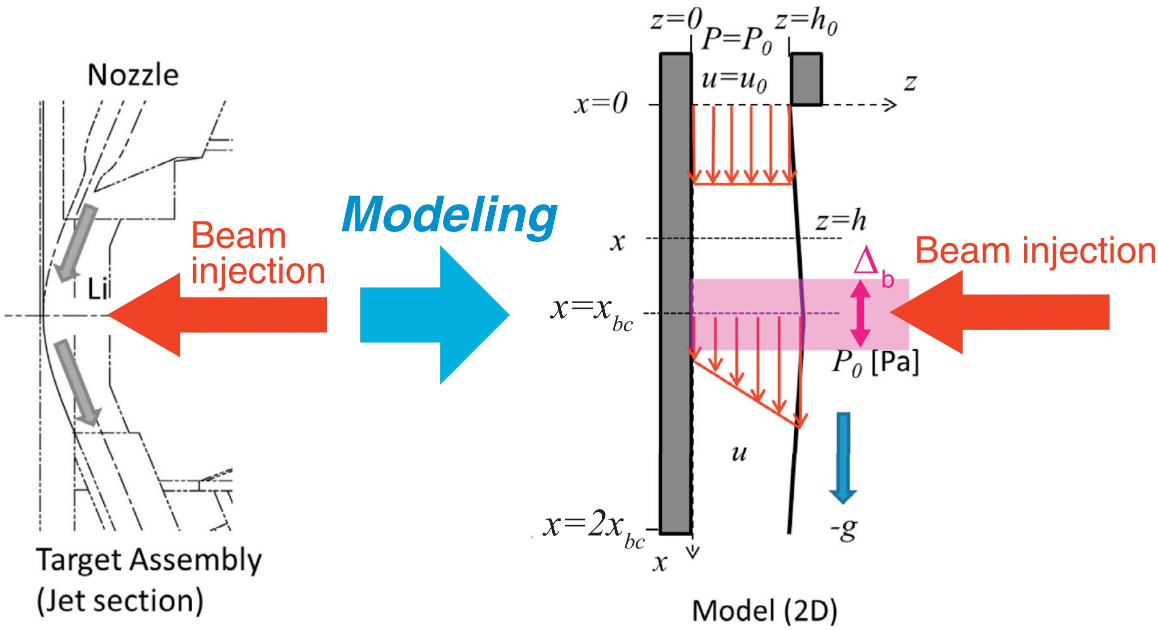

Fig. 1. Schematic of a phenomenological 2-D model of the liquid lithium flow of the "beam-on" target.

liquid Li target of IFMIF, but its impact on the form of the free surface target was not analyzed systematically.

A purpose of this paper is to present an analytical approach to evaluate the deformation of the liquid Li target with the free surface created by the intense beam injection. We will also present a preliminary evaluation, using the analytical formula newly derived, of the thickness of the "beam-on" target under the present design condition of A-FNS.

2. Modeling and formulation

A basic idea of the analytical approach presented here is to extend the phenomenological 2-D model of the liquid Li flow of the ELTL target [13] so as to incorporate the beam injection effect to the Li flow, i.e. the force applied to the beam injection region by the energetic beam particles. A schematic of the model is shown in Fig. 1. Newly introduced in this study is the beam injection region, the height of which is represented by Δ_b in this figure.

A procedure of the analytical approach is summarized as follows:

1. Model the pressure distribution of the liquid Li,
2. Model the flow velocity distribution of the liquid Li,
3. Derive the coefficients appearing in the model velocity distribution by solving Bernoulli's equation, and
4. Derive the distribution of the thickness of the Li target in the flow direction.

The goal of the analytical approach is to derive a practical formula to calculate the distribution of the thickness of the Li target in the flow direction. It should be noted that transformation of the 2-D Cartesian coordinate to the (x, z) coordinate is not performed in the above procedure, where x and z are the coordinates of the flow and depth directions, respectively, as shown in Fig. 1. In other words, neither factors nor terms resulting from the coordinate transformation are explicitly included in the present modeling.

2.1. Pressure distribution of the liquid Li target

We propose a model of the pressure distribution of the liquid Li target by adding a new term, representing the pressure due to the beam injection, to the existing pressure model of the ELTL Li target [13]. We present a new model of the pressure, $P(x, z)$, of the "beam-on" liquid Li target as

$$P(x, z) = P_0 + P_c(x, z) + P_b(x, z), \tag{1}$$

where P_0 the static pressure, P_c the pressure due to the centrifugal force, and P_b the pressure, newly introduced, due to the force applied by the beam injection.

The "centrifugal" pressure term P_c was already derived in [13] as

$$P_c(x, z) = \begin{cases} \rho\frac{u_0^2}{R}(h - z)\frac{x}{x_{bc}} & (0 \le x \le x_{bc}) \\ \rho\frac{u_0^2}{R}(h - z)\left(2 - \frac{x}{x_{bc}}\right) & (x_{bc} \le x \le 2x_{bc}), \end{cases} \tag{2}$$

where ρ is the density of the liquid Li, R the radius of curvature, h the thickness of the liquid Li target, and x_{bc} the position of the beam center in the x coordinate. It is noted again that the deformation of the liquid Li surface caused by the centrifugal force was previously observed in the ELTL experiments [13].

Newly introduced in this study is the pressure due to the force applied by the beam injection, P_b. Consider the force balance equation of the Li target at the beam center of $x = x_{bc}$ in the z direction in order to derive P_b as

$$\left.\frac{dP(x, z)}{dz}\right|_{x=x_{bc}} = -\rho\frac{u_0^2}{R} - \frac{j\sqrt{2m}}{e}\frac{d\sqrt{E}}{dz}, \tag{3}$$

where j is the current density of the beam, m the mass of the beam particle, i.e. deuteron in this case, e the electric charge carried by the beam particle, and E the beam energy. While the 1st term on the RHS of Eq. (3) represents the centrifugal force, the 2nd term does the force of the injected beam. The negative signs in the RHS mean that the directions of the two forces are anti-parallel to the unit vector of the z coordinate. Integrating Eq. (3) under the boundary condition of $P(x, h) = P_0$, the formula representing P_b is derived as follows;

$$P_b(x, z) = \begin{cases} \frac{j\sqrt{2m}}{e}(\sqrt{E_0} - \sqrt{E_z}) & (x_{bc} - \Delta_b/2 \le x \le x_{bc} + \Delta_b/2) \\ 0 & (\text{otherwise}), \end{cases} \tag{4}$$