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High speed lithium flow experiments for IFMIF target

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Abstract

Lithium flow was tested in a free surface test channel under pressurized or evacuated condition for the IFMIF target. The test channel, with a two-staged contraction nozzle designed after water test, was newly added to the Li loop facility in Osaka. Stable flow was obtained at the velocity of up to 13.8 m/s in 0.15 MPa, and up to 8.5 m/s at medium vacuum condition. In the course of circulation, wakes on free surface were begun to be observed due to small adhesives on the channel wall. These from the nozzle edge are considered to be prevented by keeping the edge clean. Those from the corners of the nozzle and sidewall were also observed. The shape was found to agree well with the theoretical prediction, Wake shape was estimated for IFMIF geometry, and it was indicated that the wakes emerge from the corners will not disturb the presently designed beam region.

1. Introduction

International Fusion Material Irradiation Facility (IFMIF) uses liquid lithium as the target. It flows down along a concave back wall at a velocity of approximately 15 m/s. This flow is bombarded by deuteron beams of 40 MeV, whose center is located 175 mm downstream from the nozzle. Stability of the lithium flow is a major design issues. The heat generated by the deuteron beams has to be removed while preventing boiling or excessive evaporation. Any alteration of the target thickness or amplitude of surface waves should be minimized, because these directly affect uniformity of the neutron field. To satisfy those requirements, lithium flows at a speed of approximately 15 m/s on a concave channel with a radius of 250 mm. But high speed free surface flow is well known to be very unstable irrespective of the shape, thus experimental validation of the target flow is very important. However there are few studies on lithium flow with free surface.

Lithium free surface flow in vacuum was first studied by Hassberger [1,2], for the target of Fusion Material Irradiation Test (FMIT) Facility. Design of IFMIF started from the FMIT study, and a two-stage contraction nozzle was designed in Japan Atomic Energy Research Institute (JAERI). Water tests were conducted with this nozzle and indicated superiority of the new design [3,4]. However, the water flow can not simulate the influence of material properties such as surface tension, wall wetting, and effects of erosion and corrosion of structures on the surface stability. The lithium flow experiments were thus initiated using the lithium loop facility at Osaka University. In the present report, surface wakes generated from the nozzle and experimental results of surface wake shapes are described and compared with theory.

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2. Experimental

The present experiment was carried out with the lithium loop at Osaka University. The loop consists of an ALIP type electromagnetic pump (EMP), two test sections and void separation tanks, an air cooler module, and an electromagnetic flow meter. The loop uses 2 in. diameter 304 stainless steel tubing.

The free surface test section is shown in Fig. 1. This includes a honeycomb section and three perforated plates, the two-stage contraction nozzle, and a 70 mm wide flow channel. The channel is placed horizontally in order to change velocity from stagnant to more than 15 m/s. The nozzle consists of two contractions section whose ratios are 4 and 2.5, lengths are 117 and 43 mm, respectively. This is shown in Fig. 2. The nozzle geometry is almost the same as the JAERI design. Three view ports for observation of the free surface are provided at the top of the chamber covering the flow channel.

Flow tests were performed at the pressure of 0.15 MPa in argon. This allowed the inner surfaces of view ports glasses to be continuously swept by argon gas flow to maintain clarity. In the case of IFMIF, the lithium flows under vacuum conditions. The flow test under vacuum condition can be performed in this loop, but is not treated in this report. Friction between argon and lithium was evaluated, and found that Kelvin–Helmholtz instability will not take place in the present condition. The loop temperature was kept at approximately 573 K in order to avoid accidental freezing of the lithium at the point 453.7 K.

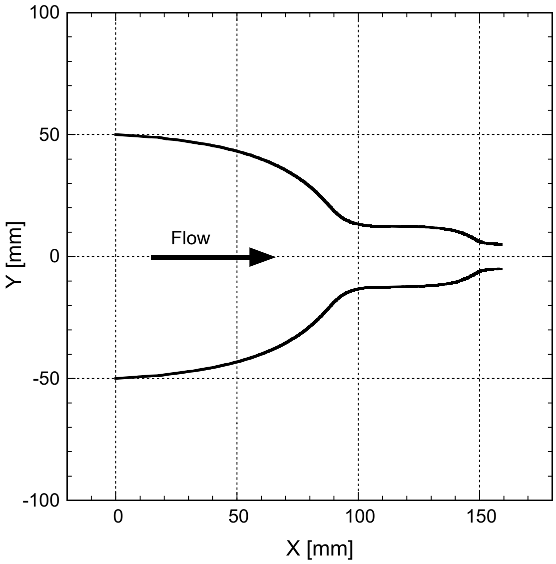

Fig. 2. Cross sectional geometry of reducer nozzle.

3. Experimental results and discussion

Free surface flow experiments for velocities ranging to 13.8 m/s at pressure of 0.15 MPa and up to 8.5 m/s for

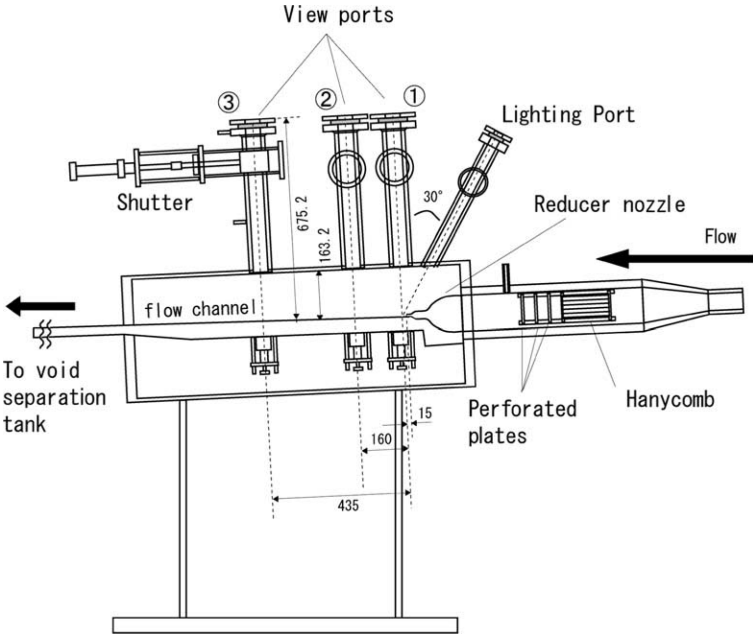

Fig. 1. Cross sectional view of free surface test section.

vacuum condition have been completed with the facility. Fig. 3 shows pictures taken by a digital camera at the first view port from the nozzle. These show free surface flows at speeds of 5 and 10 m/s. Lighting was by a metal halide lamp of 150 W from the lighting port. The exposure time was 1/256 s. Moving distances of waves are 20 and 40 mm during exposure respectively. Hence, small waves were not captured in the pictures. We can recognize ridges generated at slight angle to the flow direction. This longitudinal disturbance is called the surface wake, and the similar surface disturbances were reported by Hassberger [2]. The spots denoted by A–C are lithium drops stuck on the edge. These drops were not removed by the flow. The spot denoted by D is the corner of the edge and side wall. Wakes from the spots like A to C can be prevented by keeping the edge clean, but wakes from corners were observed even when the edge was clean, and are expected to be generated in the case of IFMIF. It was observed that the surface wakes did not vary temporally or spatially. With an increase of velocity, the angle of the ridges to the flow direction decreases.

The wake shapes in the pictures can be compared to theory. Lamb [5] discussed analysis of surface wake shape accompanying a ship (pressure point) moving on X–Y plane on clam water. It is given that it moves in the negative direction with velocity V along the axis of X, and that at the instant under consideration it has reached the point O. In our case, point O corresponds to a wake generating point and does not flow, instead the fluid flow makes on equivalent case.

The parametric equation describing equi-phasal line of the wake as a function of the wavelength of the waves is

$$p = n\lambda, \tag{1}$$

where n is an integer, p is the distance between a point on the wake, and an origin of disturbance which aligns the symmetric line of wake. Wake shape are traced by the equation

$$x = p\cos\theta - \frac{\mathrm{d}p}{\mathrm{d}\theta}\sin\theta, \quad y = p\sin\theta + \frac{\mathrm{d}p}{\mathrm{d}\theta}\cos\theta, \tag{2}$$

where λ is wavelength and θ is the angle between the ray p and the axis of X. θ follows the relation

$$\theta = \arccos\left(\frac{c}{V}\right), \tag{3}$$

where c is the wave velocity of wake components. The parameter p changes by an integer wave length value in passing from one wave-ridge to the next.

In this case, the wake is seen to be influenced mainly by surface tension, and the influence of gravity could be neglected, since wavelength of waves generating in these experimental condition are predicted to be several millimeters based on the water experiments [4]. The dispersion relationship of capillary wave is given by

$$c = \sqrt{\frac{2\pi\sigma}{\lambda\rho}\tanh\frac{2\pi D}{\lambda}}, \tag{4}$$

where ρ is the density, σ is the surface tension and D is the depth of the fluid. In our case, the fluid depth D is 10 mm, and is considered to be several times longer than the wavelength. Hence the hyperbolic tangent could be assumed to be unity, and Eq. (1) is rewritten by substituting Eqs. (3) and (4),

$$\frac{n}{p} = \frac{V^2\rho}{2\pi\sigma}\cos^2\theta. \tag{5}$$

The solid line in Fig. 4 shows surface wake shapes estimated from Eqs. (2) and (5) for $n = 0.1$, 0.4 and 1 at the velocity of 5 m/s.

There are some origins of wake at the nozzle as shown in Fig. 3. The wake shape noted circled by dashed

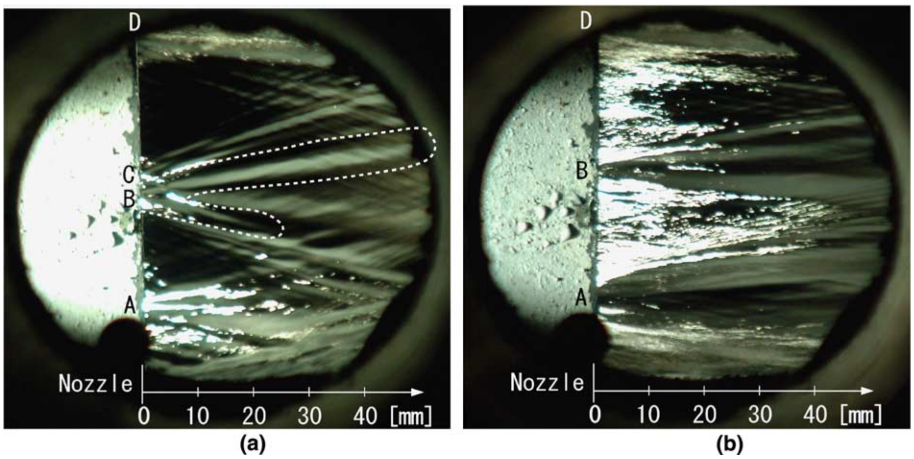

Fig. 3. Surface wakes observed during Li flow testing. (a) $U = 5$ m/s and (b) $U = 10$ m/s.

line was studied, because it comes apparently from the origin B. To measure the shape, gray value distributions of the wake in the picture were counted across the flow direction. The dashed line in Fig. 5 shows the gray value distribution at $X = 15$ mm. The Y values of the full width at half maximum are plotted by squares for the insides and circles for the outsides in Fig. 4. The measurements were made at 5 mm intervals to the flow direction. As shown in Fig. 4, bright lines of wake are equivalent in the region of $n = 0.1$ to 0.4 in the theory.

The number n denotes phase of wake, and $n = 1$ corresponds to 2π. Sinusoidal wave whose phase of Y direction changes same as Lamb's theory at $X = 15$ mm is shown in Fig. 5 by solid line for the purpose to show the phase variation. The wake is considered to be produced by obstacles attached on the upper surface of the nozzle throat. Therefore, the amplitude -1 is used at $Y = 0$.

Bright region in Fig. 3 correspond to slope up to $n = 0.5$. The region show reflected light from the slopes on good inclination. Thus the theoretical prediction may agree well with the experimental wake shapes in the lithium flow. At the velocity of 10 m/s, the measurements were not made, because there were many saturation parts of gray value in the picture and it was impossible to measure systematically.

Shapes of the wake from the corner are difficult to recognize, because the origin of the wake and corresponding ridge could not be identified. However, there is no significant difference between the shapes from the corner and the edge as shown in Fig. 3.

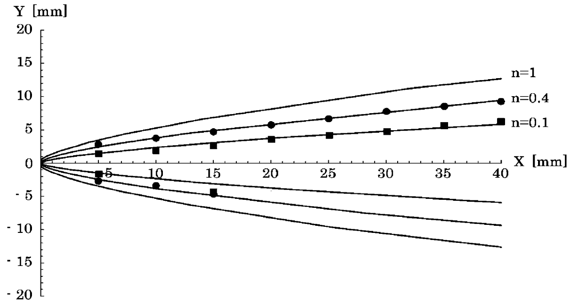

Fig. 4. Comparison of analytical and experimental results at velocity of $U = 5$ m/s.

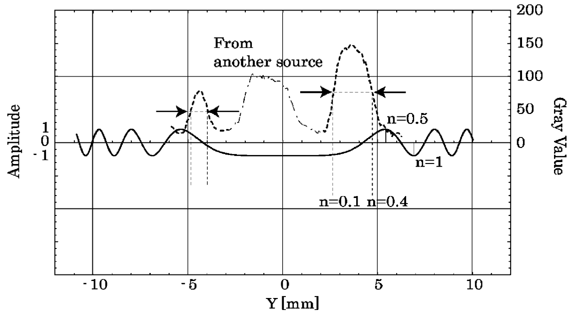

Fig. 5. Sinusoidal wave whose phase of Y direction changes same as Lamb's theory at $X = 15$ mm.

4. Predicting wake shape in IFMIF

Lithium flows along the concave wall with curvature radius 250 mm at the velocity of 15 m/s for IFMIF. Prediction of the possible wake shape in IFMIF condition was attempted. Following Hassberger [2], considering the centrifugal acceleration and the surface tension, parameter p could be described by the relation

$$\frac{m}{p} + \frac{p}{m} \tanh \frac{2\pi D}{\lambda} = \frac{V^2}{\sqrt{\frac{\sigma V^2}{R\rho}}} \cos^2 \theta, \tag{6}$$

where R is radius of curvature, $m = 2\pi\sqrt{R\sigma/V^2\rho}$. The wavelength is small compared with the fluid depth. Thus the hyperbolic tangent could be unity. The wake shape described by Eqs. (2) and (6) is shown in Fig. 6 for $n = 1$ at the velocity of 15 m/s. The lines denoted as capillary and centrifugal are the parts dominated by the surface tension and centrifugal acceleration. The capillary wake dominates the centrifugal wake to approximately 600 mm downstream from the nozzle.

In the current design, the center of the region irradiated by the deuteron beams is located 175 mm downstream from the nozzle. The region is a rectangle of $200\text{W} \times 50\text{H}$ mm, and the width of the lithium flow is 260 mm, hence there are 30 mm margins from each side wall. As shown in this figure, the first ridge of the wake from the corner is not expected to get across the irradiation region. Ridges at larger n may possibly reach the region, but those will have apparently small amplitude as shown in Fig. 3 and are not expected to give significant effect to the region. These analyses will be confirmed by planned experimental measurement of the wake heights.

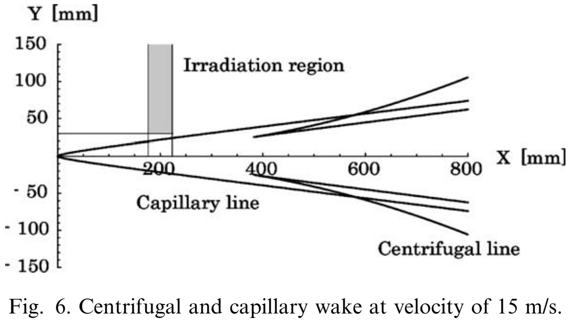

Fig. 6. Centrifugal and capillary wake at velocity of 15 m/s.

5. Conclusions

Free surface flow experiments the velocities ranging to 13.8 m/s at pressure of 0.15 MPa and to 8.5 m/s in vacuum condition have been conducted with the lithium flow loop facility. In the course of the experiments, surface wakes were observed from both the nozzle edge and the corner. The analytical results for wake shape were compared with experimental wake shape. The results showed good agreement. The sources of the wakes from the nozzle were likely caused by chemical compounds of lithium attached to the nozzle edge. The wakes can be prevented by maintaining a clean edge. Those from the corner may be caused by complicated flow in the corner, and will appear in the case of IFMIF. Wake shape with centrifugal acceleration in the IFMIF target geometry was predicted, and indicated that wakes from the corner were not expected to reach the irradiation region. Wake height measurements are planed in the near future.

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