Free-Surface Fluctuation at High Speed Lithium Flow for IFMIF

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Abstract. Lithium target flow experiment is conducted at Osaka University, for International Fusion Materials Irradiation Facility (IFMIF). The test section is approximately 1/2.5 of the IFMIF loop in scale, and a plane jet of 10 mm in depth and 70 mm in width has tested in the velocity range of up to 15 m/s using a two stage contraction nozzle. In the present paper, surface wave measurement by electro contact probe is reported. Surface fluctuations were first measured in Li flow, and the results indicate Gaussian like amplitude profiles in surface wave. The profile's tail extends to 2.2mm at most at the velocity of 15m/sec in the case of our horizontal test channel. These amplitude data was tested with the linear stability theory developed in the water experiment and found to agree with the present Li experimental data.

1. Introduction

International Fusion Materials Irradiation Facility (IFMIF) is a D – Li neutron source to produce high energy neutrons to test materials for a fusion reactor. Liquid metal lithium will be employed as the beam target. This target is panned to be 25mm thick and 260mm wide plane jet flow, which flows along a concave back wall with curvature radius of 250mm [1,2]. The Li fluid flows at a speed of approximately 15m/s in vacuum environment of 10^{-3}Pa in very stable condition. Stable flow can be realized with using a well designed contraction nozzle, and was tested in the present experiment following the water experiment at JAEA. The result indicated that flow is stable up to 15m/s under Ar environment verifying the validity of the current nozzle design.

However, in the current design, target flow is required to be very stable with surface waves of about 1mm in amplitude at velocity of 15m/s. Thus the knowledge of surface fluctuation is important in predicting the neutron flux and mechanical design of the target.

The present paper reports on the study of surface wave fluctuations. An experiment was conducted with the horizontal straight Li flow channel. Surface fluctuations were mainly caused by surface waves and were measured with the electro-contact probe apparatus. This probe was inserted onto the Li surface, and contacts between probe and surface were detected and recorded. At the same time, pictures of waves on the surface were taken by a CCD camera and micro flash stroboscopic light source. Attenuation of the wave amplitude by centrifugal force was estimated. Surface waves on the IFMIF target along the concave back wall were estimated basing on the experimental results.

2. Experimental

The experiment was carried out with using the Li loop facility at Osaka University. The main loop consists of an Annular Linear Induction Pump (ALIP) type of electro-magnetic pump, an electro-magnetic flow meter, an air cooler, a void separation tank, and a free-surface test section. The daughter loop is provided with an air cooled cold trap to remove oxides form bulk lithium. The loop is consisted of 50mm tubes of SUS304 and the inventory of the Li in the loop is 0.42m^3. The whole view of the loop is shown in Fig.1 and the loop schematics in Fig.2.

The free-surface test section consists of a flow strainer, a double-reducer nozzle, view ports, and a 70mm wide straight flow channel as is shown in Fig.3. The nozzle used in the test is a 1/2.5 scale model of the IFMIF nozzle and produces a flat plane jet of 10mm thick and 70mm wide. The nozzle parts are shown in Fig.4, where the left part is that of bottom half and the right part upper half, just before assembly. The flow channel of the IFMIF target section is planned to be placed vertically, while the one of the Li loop facility of Osaka University is placed horizontally. This is mainly because the facility can be simplified, and gravity force is negligible on the stability of flow in case of high speed flow.

FIG.1. Experimental Facility

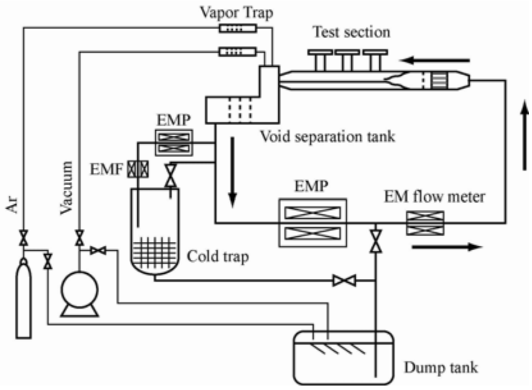


FIG.2. The schematics of the loop

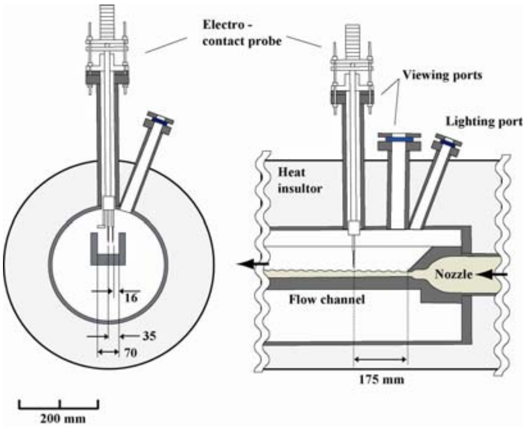


FIG..3. Cross sectional view of the test section, nozzle and probe port.

FIG..4. Upper and lower halves of the nozzle

An electro-contact probe apparatus was employed, to directly measure the waves on the free-surface. A picture of the apparatus is shown in Fig.5. This apparatus were provided with two probes a calibration plate of the probe position, and a motor driving mechanism. Two probes move together, but are electrically independent. A signal detection circuit of TTL logic was used. Either probe contacts with Li surface, the circuit including the probe and surface is shorted electrically and a voltage drop is detected.

This probe apparatus was installed on the view port of the test section shown in Fig.3. This port was located 175mm downstream from the nozzle exit, corresponding to the center axis of the deuteron beam irradiation in the case of IFMIF. One probe located 16mm (about quarter of flow, CH1) and the other 35mm (center of flow, CH2) from the side wall of the channel. Probe signals were recorded through the signal detection circuit by using a PCM recorder. After flow velocity was adjusted, the apparatus was inserted from upper to lower side with a moving step of 0.1mm, until probes were completely soaked in Li. Probe signals were started to be recorded at the 0.1~0.2mm upper form the position where signals began to be detected. The flow velocity was varied from 1m/s to 15m/s under the cover gas pressure of 0.13MPa in an argon atmosphere at Li temperature of 300C.

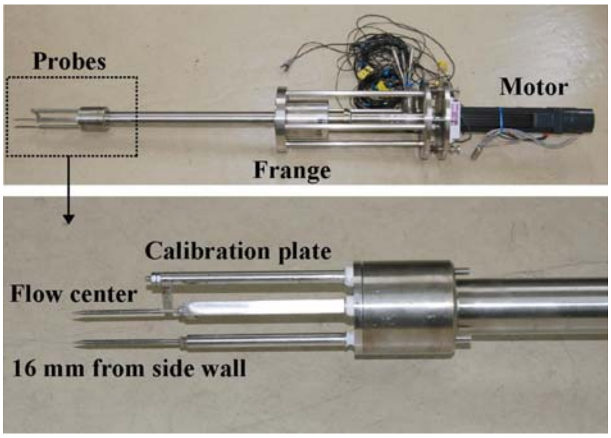


FIG.5. The electro-contact probe apparatus

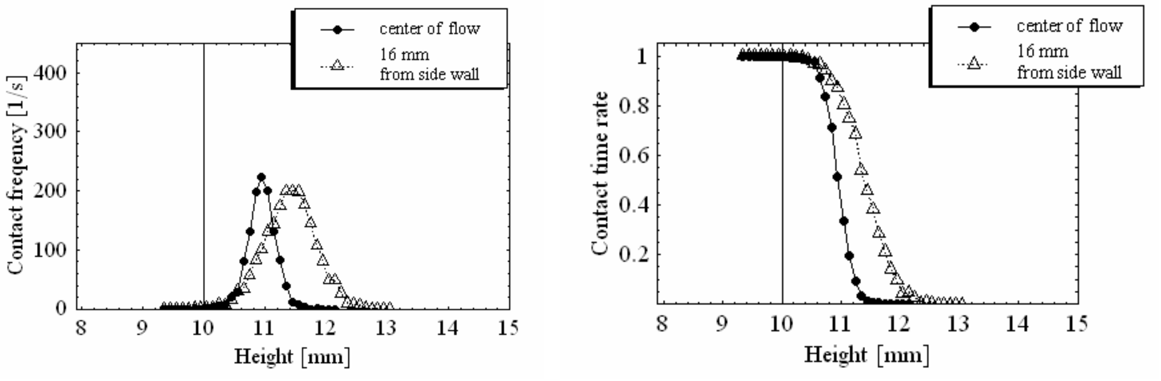
3. Experimental results

Measurement of the free-surface fluctuation by an electro-contact probe

The electric signals were ON/OFF flapping signals, corresponding to touching to the surface. Contact frequencies were calculated statistically, as the number of change from contact to non-contact per unit time. The data of the first 5sec of the recorded data was analyzed, because those of 5sec contains ample amount of the number. A typical result is indicated in Figs.6. The figure (a) shows the calculated contact frequency is indicated as a function of the probe height at the velocity of 10m/s. Nozzle height was 10mm and is indicated by the thin line. The solid circles denote the signals at the center and blank triangles at the quarter. In the case of the center probe, it begins to touch the fluid at around 13mm and frequency of ON/OFF flap is highest at 11mm and the frequency decreases as the probe is inserted further down. It continuously touched to the fluid at 9.5mm of height.

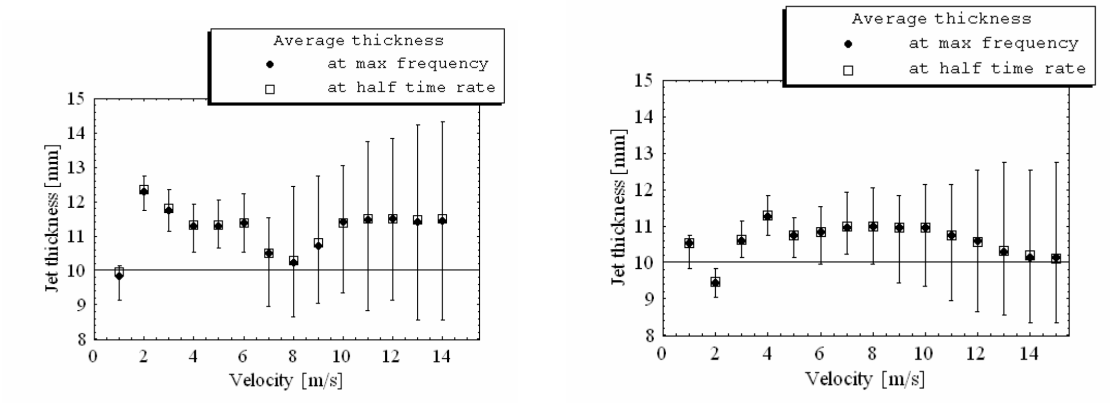
Figure 6(b) show the same data as the touching time of the probe per unit time, where the vertical value of 1 denotes the complete contact to the fluid and 0 no contact. In both representations, the profile could be considered to directly correspond to the wave shape. And it is noted that the average thickness is 11mm with the whole wave swing of 9.4mm to 12.5mm. The amplitude is less than 0.5mm if it is measured at 10% maximum. The profile has long tail off. If wettability of the Li and the probe tip were very good, the profile may be considered to have a long tail off like this. The difference in wave width between the center and quarter may be attributable to effect of wakes generated at the corner of the nozzle exit. The beam foot print is designed to be free from this effect.

In these figures, the peak in frequency (a) and 50% height of contact time rate (b) are considered to the center of the fluctuation or the waves, or the averaged height of the fluid. These values are plotted in Figs.7 as a function of flow velocity. In the figures, the plots and bars denote the fluid heights, and the whole upper and lower wave profiles respectively. From comparison of the surface photographs, it is concluded that the larger fluctuation in Figs.7 is attributed to the effect of wakes mainly from the nozzle corners.



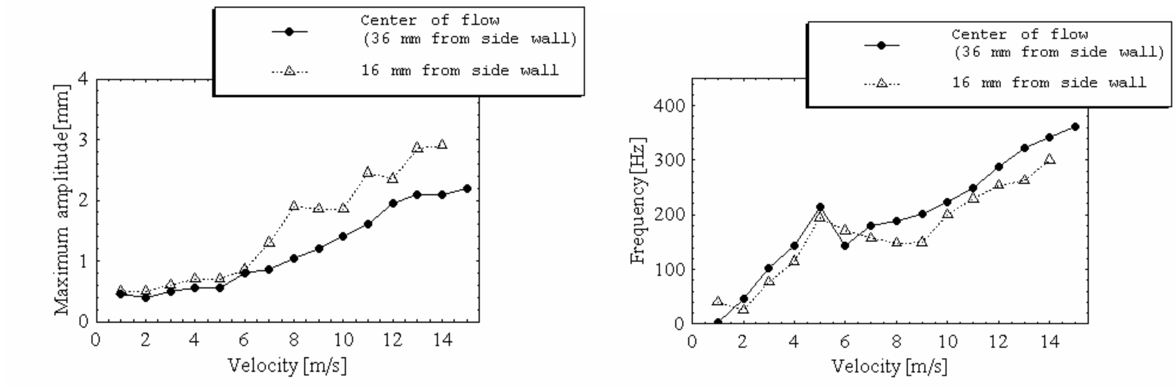
(a) *(b)*

FIG.6. Contact frequency (a) and time rate (b) at the velocity of 10 m/s



(a) 16 mm from side wall *(b) center of flow*

FIG.7. Variation of the fluid thickness and range of the fluctuation



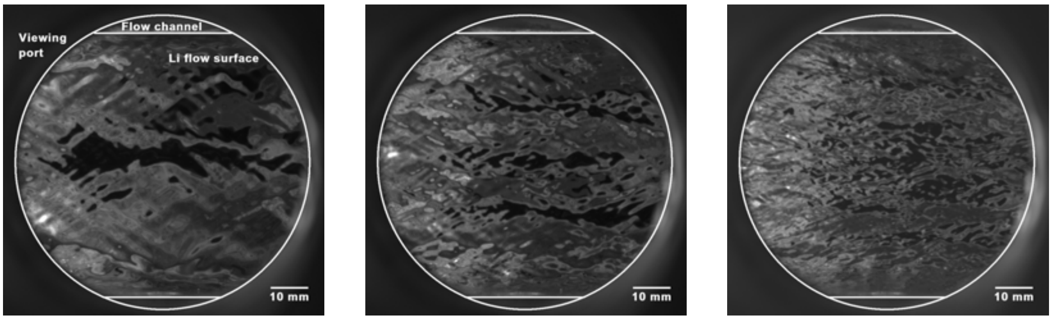
(a) Maximum wave amplitude *(b) Contact frequency*

FIG.8. Variation of the wave amplitude as a function of velocity

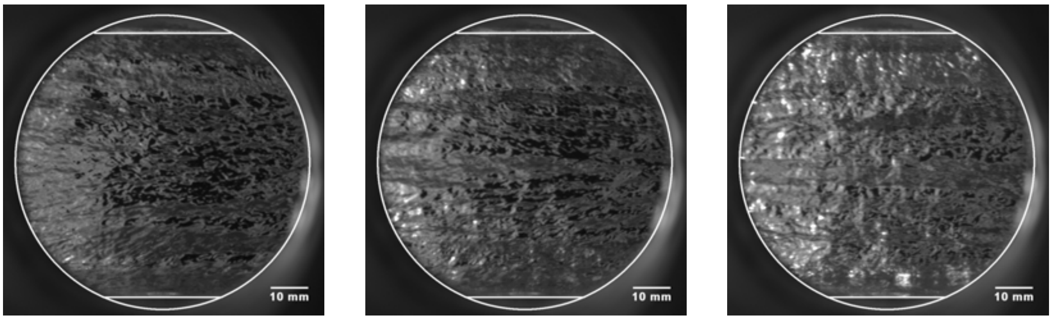
It was found in the visual observation that the nozzle edge was damaged and became serrated after lithium flowing of 1300hrs. The result of surface waves indicates slightly serrated nozzle edge and resultant surface wakes in the stationary wave pattern.

The obtained maximum amplitude and the contact frequencies are plotted in Figs.8 as a function of the velocity. The solid circles denote those at the center and blank triangles at the quarter. From Fig.8(a) it is noted that the wave glows gradually in amplitude with an increase of the velocity, but seems to saturate above 12m/s, and reaches 2.2mm of half amplitude at 15m/s. This amplitude is estimated to be less in the case of the actual target, because of the centrifugal force which is much stronger than gravity force of the present horizontal channel[5,6].

In the case of Fig.8(b), it is seen that the wave characteristics are divided into three regions at 5m/s and at 9m/s. In the region below 5m/s, the surface is very stable and the fluctuation is very small, which is also shown in Figs.9(a),(b).



(a) 2 m/s *(b) 3 m/s* *(c) 5 m/s*



(d) 7 m/s *(e) 10 m/s* *(f) 15 m/s*

FIG.9. Pictures of the Li flow surface

In Figs.9 stroboscopic photography of the Li surface at 175mm downstream from the nozzle exit are represented. Above 5m/s to 9m/s, two dimensional waves are generated [4] in the vicinity of the nozzle exit, and result in a gradual increase in amplitude and almost constant frequency in waves (Figs.9(c),(d)). Above 9-10m/s, the two dimensional waves disappear instead random waves are generated. The flow is thoroughly random as are shown in Figs.9(e),(f).. The wavelength of surface waves could be accounted from these photos, and are approximately 2 to 3mm in the case of 15m/s. These characteristics has been observed in water free surface flows, and analyzed by theory, but first demonstrated in this experiment that the water theory agrees with lithium flow.

4. Discussion

Non-dimensional amplitude of the fluctuation

Stability of shear layer under free surface was studied analytically and compared with water experimental results in Ref[7]. This study indicated that free surface instability may be described by the Weber number with using the shear layer thickness as its characteristics length, and that most instable frequency which was derived from the stability theory, agreed well with measured the most unstable frequency in the water experiment. The growth of wave amplitude was also predicted by the linear theory. If this study is applied to the present case, the probe results could be analyzed by the Weber number, though the probe measurement was conducted on an axis 175mm downstream of the edge where is far downstream of the instable region due to shear layer. The Weber number We_Δ described by the shear layer thickness Δ as characteristics length can be described as,

$$We_\Delta = \sqrt{\frac{{U_0}^2 \cdot \rho \cdot \Delta}{T}} \quad ,$$

where U_0 is the velocity at the outer edge of the boundary layer. This value can be represented by the average flow velocity, since the boundary layer is very thin. Symbols ρ and T denote the density and the surface tension, respectively. The boundary layer thickness at the nozzle exit was estimated according to [7], that is, the velocity profile inside the nozzle was calculated from the Laplace equation of the stream function of potential model, development of boundary layer momentum thickness was estimated from a method of Waltz, and development of the turbulent boundary layer from that of Buri. The boundary layer thickness was estimated from momentum thickness according to a relation,

$$\Delta = 2\delta_2 /(0.664)^2 \quad .$$

The resultant momentum thickness in the boundary layer at the nozzle exit was indicated in Fig.10.

With using these values as characteristics lengths, the maximum wave amplitude A represented previously are plotted again in Fig.11 as a function of the Weber number. The solid line is the best fit of the plots, and is described by,

$$A/\Delta = 0.278 \cdot {We_\Delta}^2 + 0.443 \cdot We_\Delta - 0.00495 \quad .$$

It is clear that the measured amplitude was well predicted by square of Weber number basing on the linear potential flow theory. This result indicates that the amplitude data obtained in the experiment will be very reproducible and consistent with previous fluid experiments. It is noted that the saturation above We of 5.5 is observed.

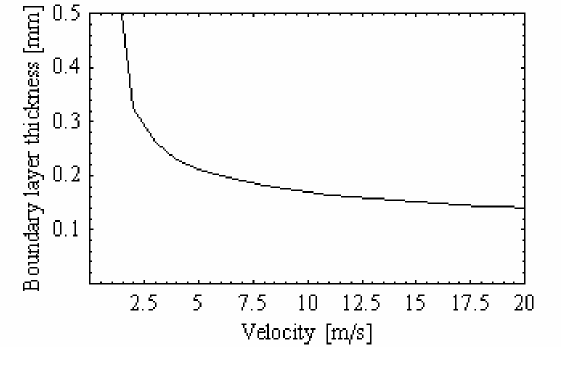


FIG.10. Boundary layer thickness at the nozzle exit against the mean fluid velocity

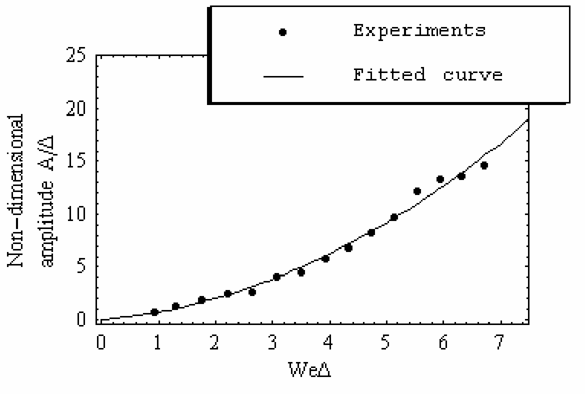


FIG..11. Non-dimensional amplitude of surface fluctuation against Weber number at the center of flow (solid line, the fitted curve)

5. Summary

The lithium loop facility at Osaka University was modified to perform high speed free surface flow experiment for IFMIF target research. The two stage contraction nozzle designed basing on the water experiment was verified in the experiment to suit for high speed flow generation. The wave characteristics on the beam axis were measured with electro-contact probes. The obtained data shows Gaussian like profiles with long tail-offs. Owing to the long tail, amplitude in wave reached 2.2mm at maximum at 15m/s. These wave characteristics were found to agree well with the linear stability theory, and validity of the present experimental results was certified.

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