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Water jet flow simulation and lithium free surface flow experiments for the IFMIF target

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Abstract

A water jet experiment was performed to investigate the influences of nozzle inner wall roughness on the free surface stability of water flow, which simulates the lithium (Li) target jet flow of the International Fusion Materials Irradiation Facility (IFMIF). The effect of a cover gas was investigated further as a possible candidate for the interfacial wave growth because of the Kelvin–Helmholtz instability. The results showed that the jet interfacial roughness was insensitive to the cover gas pressure, but it increased with the wall roughness because of the development of a boundary layer along the wall. This effect was found to be significant when the velocity was higher than 10 m/s. Utilizing these results, a Li open flow experiment is being planned by modifying the Li Loop at Osaka University.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-based Deuteron–Lithium (D–Li) neutron source to simulate the neutron irradiation field in a fusion reactor. After the IFMIF conceptual design activity (CDA) [1] in 1995–96 and the conceptual design evaluation (CDE) [2] in 1997–98, the IFMIF project proceeded to the next phase: the Key Element Technology Phase (KEP) [3] to reduce key technology risk.

In the IFMIF target, free surface liquid Li flows at high speeds up to 20 m/s to remove the significant heat loads up to 10 MW (1 GW/m^2) generated by D$^+$ beams with energies up to 40 MeV and currents up to 250 mA (125 mA × 2 beams). The stability of the flow surface affects the neutron field and irradiation conditions. Furthermore, significant flow fluctuations may affect flow integrity and long-term operating stability of IFMIF. Therefore, the flow stability is one of main issues for the IFMIF target system in the KEP.

Water flow experiments have been employed to simulate IFMIF liquid Li flow, because the kinematic viscosity of water at 20 °C (1.01×10^{-6} m^2/s) and Li at 250 °C (0.98×10^{-6} m^2/s) are similar. Both flows are nearly equal in Reynolds number under common conditions of geometry and flow velocity. (The Li average temperature is increased from 250 to 285 °C by 250 mA beam heating.) The validity of a double reducer nozzle to generate high-speed flow without separation was confirmed through water experiments conducted previously using a nearly full-scale nozzle in the CDA [4]. Measurements of velocity and pressure in a nozzle region, including boundary layers in a water flow experiment, are useful for predicting those in a Li flow

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experiment. Thermal-hydraulic analyses of the Li target stability showed that the heated Li flow would not boil [5], because the Li boiling point increases with the pressure induced by the centrifugal force in flow along a concave wall. After these experimental and analytical investigations, the main concern has shifted to the hydraulic stability of the free surface. In the water flow experiments performed previously, smooth, 2D and 3D wave regions were observed on the free surface from the nozzle exit to downstream, and they depended on the average velocity [6]. Significant instability of the free surface should be avoided to ensure reliable IFMIF operation. Therefore, the effects of nozzle condition on the surface instability should be clarified to determine the target nozzle design.

This paper describes water experiments performed at the Japan Atomic Energy Research Institute (JAERI) to clarify the effects of the inner wall roughness of the upstream nozzle on behavior of the surface waves. The results will be used to develop nozzle manufacturing specifications for subsequent Li flow experiments. Results of Li flow experiments will be utilized for the design and manufacture of the IFMIF target. This paper also describes the Li flow experiments planned as a collaboration between the National Institute for Fusion Science and JAERI, involving a modification of an existing Li test facility in Osaka University. The experiments are to be performed to investigate the characteristic behavior of liquid Li.

2. Water jet flow simulation experiment

2.1. Experimental equipment and conditions

Previous water flow experiments showed that the main cause of surface waves was a boundary layer formation along the nozzle inner wall at the upper stream of the free surface [6]. Growth of the surface wave depended on flow velocity [5,6]. Another possible cause was the pressure of the cover gas at the free surface. The water experiments in the CDE [6] were performed under a pressure of 0.1 MPa.

The water experiments in KEP were performed in JAERI using two types of test sections to investigate the effect of nozzle wall roughness on free surface stability. One nozzle had an inner wall roughness of 6.3 μm and the other a roughness of 100 μm. Fig. 1 shows a test section made of acrylic resin. The test section was placed horizontally to make free surface observations convenient. The effect of gravity on the wave amplitude was negligible for high-speed (10–20 m/s) flow, according to a linear stability analysis of surface waves. [4] This analysis also showed that the effect of centrifugal force was not significant for water and Li flows. Therefore, straight test sections have been employed to investigate such surface behavior. Through the double reducer nozzle, a water flow with a thickness of 100 mm and a width of 100 mm is reduced to a thickness of 10 mm and a width of 100 mm. A flow straightener composed of a honeycomb and multi-hole-diaphragm was installed at the upper stream of the nozzle. To maintain water viscosity, which influences the velocity distribution in the boundary layer, the water temperature was roughly controlled by regulating with city water flow. The difference in temperature between the pure and city water did not affect the velocity measurement efficiency.

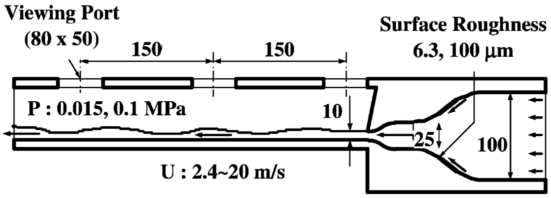

Fig. 1. Schematic cross-section of test section for water experiments (high-speed water flow is generated through a double reducer nozzle at the right side, and flows left with a free surface. This test section is made of acrylic resin for observation using a high-speed digital camera and velocity measurement using laser doppler velocimetry LDV).

The average flow velocity at the nozzle exit ranged 2.4–20 m/s in the experiments. The velocity distribution at the nozzle exit was measured using an argon laser source (Spectra Physics, Model 168-06) and a laser Doppler velocimeter (LDV, Aerometrics RSA-2000). Measurements with a resolution of 0.01 mm were performed near the wall on the free surface side to obtain data in the boundary layer. Behavior of the free surface was observed using a high-speed digital camera at locations near the nozzle exit and 150 mm downstream from the exit. The latter location corresponds to the footprint of the D^+ beam in IFMIF. The cover gas (air) pressure at the free surface ranged 0.015–0.1 MPa to investigate the effect of cover gas pressure on growth of the surface waves. The surface behavior at 0.015 MPa was observed through acrylic windows sometimes misted by splash or vapor from the water surface.

2.2. Experimental results and considerations

The effect of cover gas pressure on the surface wave growth was found to be insignificant by comparing results from the 0.1 to 0.015 MPa experiments. These experiments were the first comparing the effects of cover gas pressure. An air stream was found to flow along the flow surface. This behavior lessened, even at a pressure of 0.1 MPa, the Kelvin–Helmholtz instability caused by velocity difference between gas (air) and liquid (water). This result is useful for planning Li flow experiments, where a test section is to have a gas (Ar) phase in a closed, limited volume nearly equal to that in the water experiments. Subsequent Li experiments can thus be performed under gas-covered conditions, which is advantageous to avoid cavitation at an electromagnetic pump (EMP). The result also suggests that surface waves may occur even on the IFMIF target under a near-vacuum condition of 1×10^{-3} Pa. Therefore, the behavior of the surface wave should be clarified for continuous long-term operation of the IFMIF target system.

Utilizing the above result, the rest of the experiments were performed under a cover gas pressure of 0.1 MPa, and the surface behavior was observed without the acrylic windows. The experiments were performed using smooth (wall roughness: 6.3 μm, defined as a height between the highest and the lowest points) and rough (100 μm) wall nozzles with changing flow velocity. The wall roughness of the reducer nozzle was found to promote interfacial instability especially at a speed of 10 m/s or more in the rough wall nozzle case. The velocity range of 10–20 m/s corresponds to IFMIF operations. This result suggests that the rough wall nozzle may not be acceptable for IFMIF operation. More exact investigations of the surface behavior of Li flow will be performed in subsequent Li flow experiments.

The cause and growth of surface waves can be understood in connection with the boundary layer at the nozzle exit. Fig. 2 shows velocities near the walls at the nozzle exit. The boundary layer thickness decreases with increasing mean velocity in the smooth wall nozzle. At a mean velocity of about 20 m/s, the boundary layer thickness is about 0.08 mm (defined at a velocity 90% of the mean velocity). However, in the rough wall nozzle, the boundary layer thickness increases in the high velocity range of 10–20 m/s, while it decreases in the low velocity range up to 5 m/s. In the case of 20 m/s, the thickness is about 0.26 mm. A characteristic change was observed in the boundary layer in the rough wall nozzle above 5 m/s. Fig. 3 shows the relationship between shape factor and mean velocity for the two nozzles. The shape factor, $H12$, is given as $H12 = \delta_1/\delta_2$, where δ_1 and δ_2 are displacement thickness and momentum thickness of the boundary layer, respectively. Laminar and turbulent flows give $H12 = 2.6$ and $H12 = 1.4$, respectively, for fully developed flow between parallel plates. Significant changes in $H12$ were observed at about 5–10 m/s for the rough wall nozzle and at roughly 10–15 m/s for the smooth wall nozzle. Therefore, it can be summarized that laminar and turbulent boundary layers cause relatively stable and unstable behavior on the free surfaces, respectively. Furthermore, the characteristic change from laminar to turbulent occurs at a lower velocity with increasing nozzle roughness. Nearly the same change would occur for Li flow because of the similarities in kinematic viscosity and Reynolds number between Li and water. It can be expected that a Li flow in a rough wall nozzle would cause surface instability at lower velocity than that in a smooth wall nozzle.

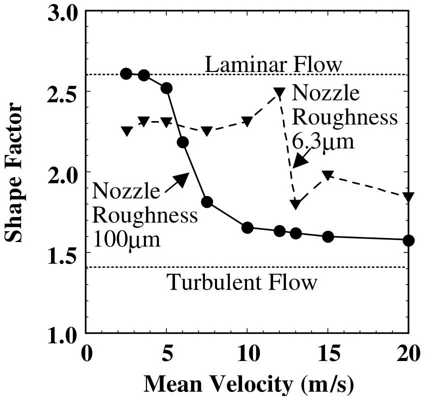

Fig. 3. Characteristic change of boundary layer (the change of boundary layer from laminar to turbulent occurs at higher velocity in the smooth wall nozzle case, while it occurs at lower velocity in the rough wall nozzle case).

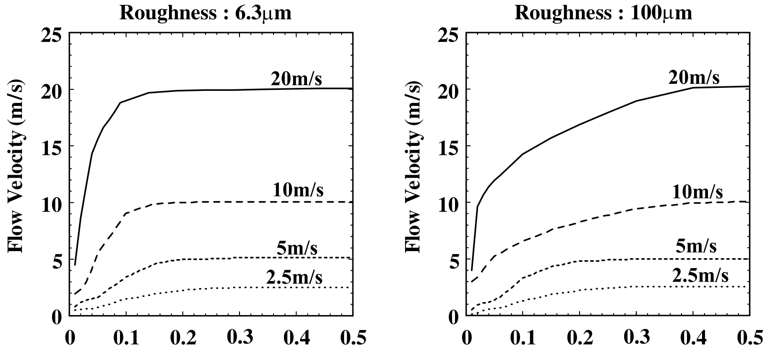

Fig. 2. Velocity distribution near wall (the left and the right graphs show velocities at the exit of the smooth and the rough wall nozzles, respectively. The boundary layer thickness decreases with increasing mean velocity in the smooth wall nozzle, while the thickness increases in the rough wall nozzle in the velocity range above 5 m/s).

These results show that the surface wave growth mainly depends on the nozzle surface roughness. The nominal value of 6.3 μm (surface roughness defined in JIS B-0601) is easily achieved by machining. This roughness is to be applied to the manufacturing specification of a nozzle made of stainless steel for use in the subsequent Li flow experiments. These results will also provide a guideline on replacement frequency for IFMIF target assemblies, because nozzle wall roughness increases due to corrosion and erosion of the stainless steel by flowing Li.

3. Preparation for the free surface Li flow experiment

Experiments with high-speed Li flow are planned under free surface conditions, to confirm the validity of the nozzle design parameters, by modifying the Li experimental facility at Osaka University with flow rates of 0.5 m^3/min at 0.5 MPa and a Li inventory of 0.23 m^3 [7]. Work will be carried out to observe the liquid surface, to study evaporation and splash of Li, to determine the cavitation characteristics of the EMP, and to measure corrosion of the nozzle surface. While the IFMIF target is to be operated under a vacuum of 10^{-3} Pa, the planned experiments will be mostly performed under gas(Ar)-covered conditions, because of the insignificant effect on the flow stability as noted above.

Fig. 4 shows the modification plan of the Li test facility. The test section and the separation tank are newly installed. To produce 15 m/s at less than 0.65 m^3/min, the double reducer nozzle was designed to have a width of 70 mm and a thickness of 10 mm. The velocity distribution of Li flow in the nozzle and in the boundary layer would be nearly the same as those in the water experiments. The temperature of the Li can be controlled at 250–500 °C.

A measurement of the Li flow thickness will be performed using a conductivity sensor with needles near the free surface. An ultrasonic or electromagnetic–ultrasonic transducers utilized on sodium loops, have been prepared. Plans also call for cavitation detection measurements using accelerometers attached at inlets of the EMP and the nozzle.

In May 2001, the control sequence of the facility was tested, and an unusual sound due to cavitation was detected under evacuated conditions and a flow velocity of 2.8 m/s at the EMP. Another water experiment was performed to validate the capability of liquid–gas separation devices, because bubbles involved in the flow are expected to block smooth flow. Though the devices were effective for separation, small bubbles of less than 0.5 mm diameter were very difficult to remove. Electron beam welding was used to investigate the deformation and surface roughness of the metal nozzle after welding.

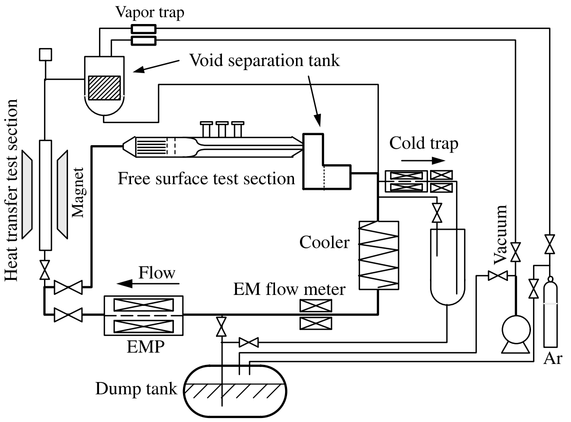

Fig. 4. Schematic view of modification plan of Li test facility (the 'free surface test section' and a 'void separation tank' will be newly installed. The 'heat transfer test section' and a 'void separation tank' near upper left corner will not used after the modification).

4. Conclusions

Water experiments have been performed featuring the parameters necessary to realize lithium flow experiments being planned. The following conclusions were obtained.

(1) The effect of cover gas pressure on interfacial wave growth at a high-speed jet free surface was insignificant for the range of pressure from 0.015 to 0.1 MPa.
(2) Interfacial wave growth mainly depends on the nozzle inner wall roughness, affecting the development of a boundary layer on the wall, especially when the average jet flow speed is high. It is necessary to confirm wave growth behavior for flowing Li which has a far larger surface tension than water.
(3) By modifying the facility at Osaka University, Li free surface flow experiments are being planned and prepared under pressurized and evacuated cover gas conditions. The surface behavior of Li and corrosion and erosion will be observed.

The results from the Li flow experiments will be utilized in the IFMIF design.

References

[1] M. Martone (Ed.), IFMIF International Fusion Materials Irradiation Facility Conceptual Design Activity Final Report, ENEA Frascati Report RT/ERG/FUS/96/11, 1996.
[2] A. Möslang (Ed.), IFMIF International Fusion Materials Irradiation Facility Conceptual Design Evaluation Report, FZK Report FZKA6199, 1999.

[3] M. Ida et al. (Eds.), IFMIF International Fusion Materials Irradiation Facility Key Element Technology Phase Task Description, JAERI-Tech 2000-052, 2000.
[4] H. Nakamura et al., in: Proceedings of 8th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH8), Vol. 3, Kyoto, Japan, 1997, p. 1268.
[5] M. Ida et al., Preliminary analyses of Li Jet Flows for the IFMIF Target, JAERI-Research 97-030, 1997.
[6] K. Ito et al., Fus. Technol. 37 (2000) 74.
[7] N. Uda et al., Forced Convection Heat Transfer and Temperature Fluctuations of Lithium under Transverse Magnetic Fields, J. Nucl. Sci. Technol. 38 (11) (2001) 936.