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Experimental and numerical studies on free surface flow of windowless target

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ABSTRACT

The formation and control method of the coolant free surface is one of the key technologies for the design of windowless targets in the accelerator driven system (ADS). In the recent study, experimental and numerical investigations on the free surface flow have been performed in a scaled windowless target by using water as the model fluid. The planar laser induced fluorescence technique has been applied to visualize the free surface flow pattern inside the spallation area. Experiments have been carried out with the Reynolds number in the range of 30,000–50,000. The structure and features of flow vortex have been investigated. The experimental results show that the free surface is vulnerable to the vortex movement. In addition, CFD simulations have been performed under the experimental conditions, using LES and RANS (k-ω SST) turbulence models, respectively. The numerical results of LES model agree qualitatively well with the experimental data related to both flow pattern and free surface behavior.

1. Introduction

Management of high level nuclear wastes receives great concerns by public nowadays. Transmutation is the fundamental approach to reduce minor actinides and long life fission products (Shuurmans et al., 2007). Accelerator driven system (ADS) is one of the most promising transmutation systems and is being researched in the worldwide (Roelofs et al., 2008a). The spallation target, usually compared to the heart of the ADS, produces primary neutron sources for subcritical core. In the early designs, the spallation target and the accelerator are separated by a solid window that ensures the vacuum safety, as shown in Fig. 1a. In-state-of-the-art, no material can survive for the desirable service duration under such high-energy proton bombardment that is also accompanied by heavy metal corrosion. Due to lifetime limitation of material, the windowless target, as shown in Fig. 1b, attracts more and more attention (Bianchi et al., 2008).

In a windowless target, the free surface of the liquid metal flow, as the substitution of the solid window, separates the spallation target from the accelerator system. The application of free surface brings in two major challenges. The first one is the maintenance of the integrality and stability of the free surface, which guarantees the vacuum safety of the accelerator system by avoiding splash of the heavy metal flow. The second one is the reduction of the recirculation flow in the spallation area, which enhances the heat removal ability of the flow pattern by decreasing the detention time of the liquid heavy metal in the spallation area. With sufficient heat removal ability, the evaporation of liquid heavy metal will not occur in the spallation area, which also ensures the vacuum safety of the accelerator system. Hence, the integrality and stability of free surface and the flow pattern in the spallation area become the most important issues in the development of ADS (Tichelen et al., 2007). In order to establish criteria for windowless target design, knowledge about the flow pattern and the free surface behavior is desired.

In the actual design, the fluid in the windowless target is heavy liquid metal, e.g. LBE. However, the operation of a LBE test facility and the measurement of LBE flows are extremely challenging. According to Roelofs et al. (2008b), thanks to the hydraulic similarity by using selected characteristic dimensionless numbers, such as Reynolds number ($Re = \rho LU/\mu$), Froude number ($Fr = U^2/gL$), Weber number ($We = \rho LU^2/\sigma$), model fluid can be used for hydraulic analysis and optimization of windowless target design. The comparison of the above-mentioned dimensionless numbers between 20 °C water and 400 °C LBE are listed in Table 1. In Table 1, the subscript "W" represents water and the subscript "M" represents LBE. As it is listed in Table 1, all three dimensionless numbers share the order of magnitude, which indicates 20 °C water can be chosen as the model fluid.

In Tichelen et al.'s water experiments (2007) with the laser doppler anemometry (LDA), precious but limited flow data were obtained, and the whole flow pattern information was not available due to the limitation of the measurement technique applied. Batta and Class (2008) performed numerical investigations on different geometries of the windowless target. Some proposals for decreasing the recirculation zone and enhancement of free surface stability were done. Up to now, there is no report about detailed

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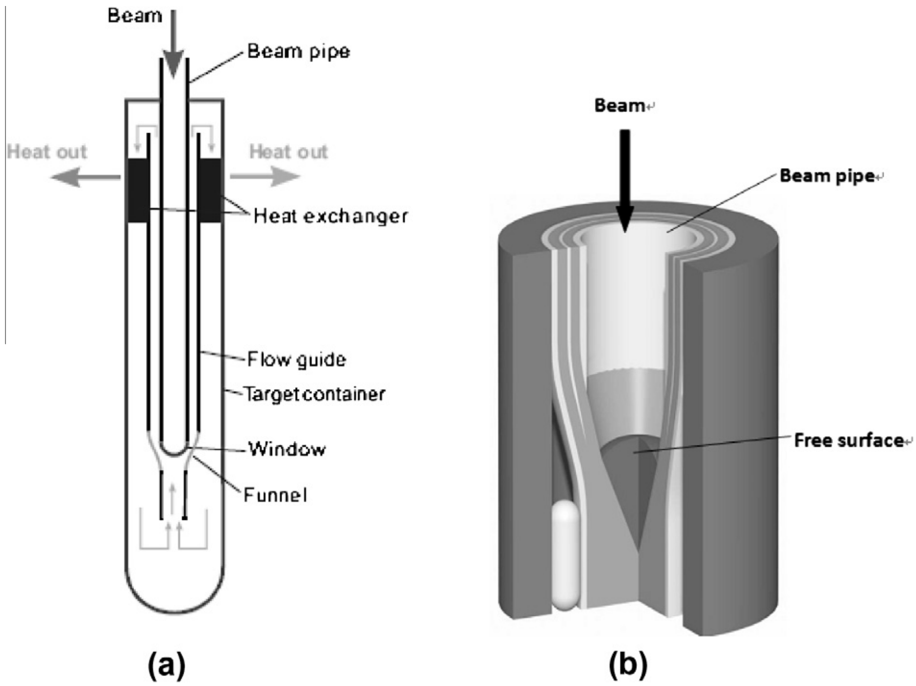

Fig. 1. Comparison of window target (a) (Cheng et al., 2008) with windowless target (b) (Roelofs et al., 2008a,b).

Table 1
Comparison of the dimensionless numbers.

Dimensionless number	Ratio
Re_W/Re_M	0.155
Fr_W/Fr_M	1
We_W/We_M	0.533

investigation on free surface behavior and flow pattern in spallation area under windowless target conditions. However, that investigation is crucial to understand free surface flows in the geometry of windowless targets and establish design criteria for windowless targets.

The present paper deals with the experimental investigation on the free surface behavior and the flow pattern in spallation area conducted in an approximately 1:1 sized windowless target model. The windowless target model refers to the design of a 50–100 MWth experimental ADS facility (XT-ADS) that is carried out within the EUROTRANS project (Batta and Class, 2007, 2008). The heat deposited in the spallation target by the proton beam of 2.5 mA current at 600 MeV reaches 1–1.5 MW (Shuurmans et al., 2007). Water has been used as the model fluid and the planar laser induced fluorescence technique has been applied for flow visualization. In addition, computational fluid dynamics (CFDs) simulations have been performed in a 45-degree slice of the windowless target. The present study are aimed at obtaining more information about free surface behavior and flow pattern in spallation area and at finding out a promising numerical method to predict the free surface flow under windowless target conditions.

2. Experimental study

2.1. Experimental approach

The experimental loop is shown in Fig. 2. Water is supplied by a centrifugal pump. And the flow rate is measured with an electromagnetic flowmeter. In order to minimize the pressure fluctuation, a 0.3 m^3 buffer tank is located at the exit of the centrifugal pump. Before the entrance of the scaled target, a heat exchanger is used to keep water at a given temperature.

The target model is in the scale of approximately 1:1, as shown in Fig. 3. The conical channel is built to be transparent for flow visualization. The parameters are improved with the inlet diameter of 138 mm, the outlet diameter of 68 mm and the conical angle of 10°. In the conical channel, the flow is mainly driven by gravity. And the free surface is formed near the exit of the model beam tube in the conical channel.

The flow pattern inside the spallation area is visualized by means of the planar laser induced fluorescence (Kumar et al., 1998). A semiconductor laser source with 2 W power continuously outputs a 523 nm single-line source laser beam. And then a cylindrical lens is used to expand the laser beam into a laser sheet, as shown in Fig. 4, which can induce fluorescence of spherical particles with mean diameter of 51.7 μm in an axial plane of the target (Tatum et al., 2007). The velocity difference between particle and water is predicted to be less than 0.1% of the inlet velocity (Zhang et al., 2004). With good quality of water following, the short tracks indicated by the fluorescence of particles can be considered as the streamline of the flow pattern. The images of free surface behavior and flow pattern are recorded by a high speed camera at the shooting rate of 150 frames per second.

2.2. Experimental results

In order to identify different experimental conditions, several parameters are introduced. Because the most concern of this study is the liquid phase, the Reynolds number (Re) is defined on water viscosity, mean velocity at the inlet annular channel and the hydraulic diameter of the inlet annular channel. The major configuration feature of the free surface is represented by surface length, which means the distance between the exit of the model beam tube and the bottom of the free surface.

Flow visualization was conducted under several flow rates. When flow rate is less than 16 m^3/h, the buoyancy of the air embraced by the free surface and the binding force of upper stream