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Computational and experimental studies of the flow field near the beam entrance window of a liquid metal target

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HIGHLIGHTS

- Water model of liquid metal target for validation of CFD models was built.
- PIV measurements showed flow features in the region near beam entrance window.
- The zones with high turbulence kinetic energy were distinguished.
- Reasonable agreement between modeling and PIV data was obtained.

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ABSTRACT

After the first world liquid metal target has been successfully operated at the SINQ facility at the Paul Scherrer Institut (PSI) for 6 months. The idea of having a reliable target with a bypass flow for cooling the beam entrance window, but with the bypass flow not driven by a separate pump, was examined within the project called LIMETS (Liquid Metal Target for SINQ). In designing of liquid metal targets, turbulence modelling is of high importance due to lack in methods for measuring the spatial distribution of flow and turbulence characteristics. In this study, validation of different turbulence models were performed in water model with hemispherical geometry using particle image velocimetry (PIV) technique. Two components of water flow velocity in plexiglas container with inner radius of 88 mm were measured in different cross sections, with the velocities varying from 1 to 10 m/s. Numerical calculations using large eddy simulation (LES) approach and Reynolds averaged Navier–Stokes (RANS) models were carried out to validate their applicability and study performance issues. Mean velocity and turbulence kinetic energy data were used for comparison of PIV and calculation results. Reasonable agreement was obtained for mean velocity data, with some discrepancies due to the limited length of the inlet tube. However, several discrepancies in turbulence characteristics were found in numerical results, especially in RANS model calculations.

1. Introduction

One important and unique activity at the spallation source facility (SINQ) in the Paul Scherrer Institute, Switzerland, was coordinated within the project MEGAPIE (Megawatt Pilot Experiment) (Wagner et al., 2008). The detailed studies involved the design, manufacturing, integral hydraulic and component testing, safety assessment and, finally, operation of a liquid metal target. Such a target is also a main component in the ADS (Accelerator Driven System) concept, where neutrons are generated from spallation reactions and are used to initiate and maintain a continuous chain reaction in a sub-critical nuclear core (Nifenecker et al., 2001).

Since the MEGAPIE project was successfully realized in 2006, the idea of having reliable, long-term operational liquid-metal targets strengthened the interest in further optimization of the pilot MEGAPIE design. As the most delicate component of the lower target container is the Beam Entrance Window (BEW), it is necessary to demonstrate that the structural integrity of the window can be maintained under all conceivable operational and accidental conditions. In the original MEGAPIE design, a unidirectional liquid-metal

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flow was enforced across the window by a bypass nozzle driven by a separate pump in order to enhance the window cooling (Fazio et al., 2008). Because the use of a dedicated bypass pump to drive the window wall jet increases the complexity and costs of the system, the idea of developing a reliable configuration without additional bypass pump directed the design efforts. Therefore, the main motivation for undertaking extensive experimental and computational studies coordinated under project LIMETS (Liquid Metal Target for SINQ) is to (i) investigate various designs of the lower target region including a BEW that would be adequately cooled by a property of tailored main flow and to (ii) analyze hydraulic, structural and thermal behavior of the target mock-up. Therefore, the pump driven bypass flow is completely excluded from the design. Some initial computational studies showed very complex 3D flow structures right above the window, which are sensitive to even small changes of the geometrical constrains such as gaps, bends, positions of directional plates and etc. Therefore, in addition to computational studies some experimental investigations were conducted in order to validate numerical results for simplified geometries and to check the design. For that purpose two large experimental facilities have been erected: the water (LIMETSW) and liquid-metal mock-ups (LIMETSLBE).

The main goal of the water experiments (LIMETSW) is to access the flow visualization and transfer this knowledge to liquid metal flow using Reynolds similarity. Only selected configurations are to be subsequently investigated during the second session with liquid metal as a working fluid (LIMETSLBE).

Although various techniques that allow the recording of the local velocity in liquid metal flows (Eckert et al., 2007) can be found in the literature, an experiment with a plexiglas model and water as working fluid was chosen due to its simplicity, price, and the possibility for using PIV (Particle Image Velocimetry) and the possibility to easily change the geometrical configurations. Furthermore, a better space and time resolution could not be obtained in the liquid metal flow even with most up-to-date sophisticated techniques like the CIFT (Contactless Inductive Flow Tomography) (Stefani et al., 2004) or neutron tomography.

This paper is devoted to the validation and verification of the CFD procedure by using experimental results from LIMETSW tests, in particular velocity measurements using PIV method for the reference BEW design. Since liquid metal test allow less flexibility and measurement possibilities, water tests are conducted and simulation approaches validates in this set-up. The experimental approach used here also allows the investigation of various BEW designs. Namely, the same mock-up can be used for further development of water-cooled rod-bundle target for the SINQ facility.

2. Choice of design for validation

In the MEGAPIE target adequate cooling was achieved by using a jet flow superimposed onto the main coaxial flow by means of a bypass nozzle. This bypass flow was directed as a steady liquid metal stream over the central part of the beam entrance window, thus eliminating the formation of a stagnation region with a weak turbulent heat transfer at the central location right above BEW. The stagnation region would be caused by the coaxial main flow, which makes a U-turn by following the hemispherical calotte contour before entering the cylindrical riser tube. In a new design the adequate cooling must be achieved by properly directing and shaping the main flow as the bypass nozzle and bypass pump are not supposed to be integrated due to the complexity and high price. For the case of a symmetrical configuration, the stagnation region at the centreline position of the BEW develops for any gap size. In order to avoid such situations, the cross section of the

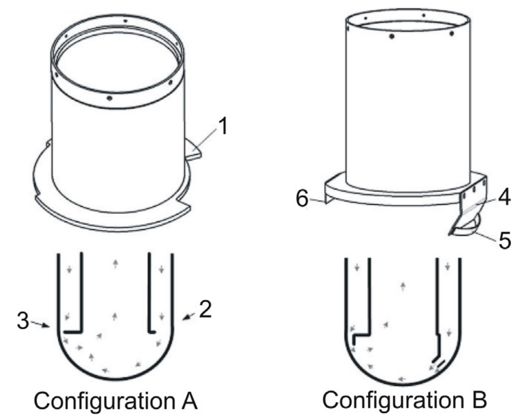

Fig. 1. Riser end configurations A and B: 1 – riser baffle; 2 – main jet opening; 3 – additional jet opening; 4 – main jet guide; 5 – turbulence promoter; 6 – additional jet guide.

annulus (gap between calotte and riser) must be asymmetrical. The second design issue is the shape of the BEW. A cusp or dome shaped windows can be considered for the final design. For the experiments a hemispherical window is chosen due to the lower costs.

In order to provide enough space for radial and axial thermal expansion of the riser (also often called guide tube) during operation, the gaps between the cylindrical part of the hull and the riser tube must be properly sized (see geometry in Fig. 1). For the case that an additional plate is used to split the side flow into two streams, we call it the turbulence promoter (Fig. 1, B, position 5). The turbulence promoter should be wide enough to allow the jet flow to cover the central region at the window with highest beam deposition and should be close enough to the window wall as the jet flow has to cool convectively the window. Such promoter (and the riser tube) will be exposed to flow- and thermally-induced vibrations; therefore they must be carefully designed and tested.

Before the beginning of the experimental phase of the project, a couple of Reynolds Averaged Navier–Stokes (RANS) based calculations were performed with the aim to identify geometries that are suitable for adequate cooling of the BEW. The velocity fields obtained from RANS simulations show the complexity of the flow field and its dependence on various geometrical parameters and configurations. However, results of these preliminary studies will not be shown here.

After an examination of several initial configurations the final reference geometry (configuration A) was designed for validation of the CFD (RANS and LES) calculations. It consists of a ring with a 60° gap (Fig. 1, A, position 1), which is welded to the riser end. There is almost no gap between the outer wall and raiser baffle. Even though this geometry does not meet the criteria for real liquid metal targets as the opening for the incoming flow is relatively far away from the spherical window, it was extensively investigated because it meets the following requirements: simplicity, convenience for a fabrication and good accessibility for the PIV technique. We distinguish the configuration A1, which has only one main jet opening and configuration A2, which has an additional jet opening on the opposite side.

In order to make a first step toward the development of a one-pump target system, additional measurements were made for the geometry with a longer riser and for flow conditioners that are closer to the spherical surface. In this geometry (configuration B, proposed by I. Platnieks, Institute of Physics, University of Latvia), the turbulence promoters are welded to the plate (Fig. 1, position 5,). A smaller gap is located on the opposite side with a smaller plate