International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

PIV Validation of Numerical Models for Turbulent Flows in a Water Test Section for Liquid Metal Target

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Abstract

A spallation reaction is used in various branches – material investigation, medicine and fundamental research. In powerful installations of this kind, a large amount of heat is generated, consequently, the heat removal from the active zone is one of most important factors in optimizing a liquid metal target design. This work presents PIV (Particle Image Velocimetry) measurements, which were carried out in a specially designed test section with water as a working fluid. Obtained data ensure reliable experimental validation of numerical calculations performed by RANS (Raynolds Averaged Navier Stokes) and LES (Large Eddy Simulation) approaches. Experimental results show zones of extensive turbulence energy generation, which is in good agreement with theoretical concept. Numerical RANS results show imperfections of the widely used turbulence models, while numerical LES results describe thoroughly investigated processes.

Introduction

Since the first spallation neutron source (SNS) was built in 70s in USA, great amount of work have been invested in this field. Nowadays in many institutes and research centres all over the world, neutron beam users can do their investigations in physics, chemistry, biology, material science, medicine branches etc. The list of disciplines where neutrons can be applied is long; furthermore, scientists are examining new application fields for studies with neutron beams. A demand for neutron beam time is already high and it is expected to grow in the future. For that reason research in this direction is under continuous developing and new high-power facilities are planned to be built in the future (for instance, ESS – European Spallation Source).

In development of MEGAPIE (Megawatt Pilot Experiment) liquid-metal spallation target, which was the first 1 MW LBE (Lead Bismuth Eutectic) target operated in the SINQ spallation neutron source facility at PSI (Paul Scherrer Institut), the design process was carried out by using experimental data and numerical results [1]. Liquid metal experiments provided data on the heat transfer coefficient near target walls. This part is usually called Beam Entrance Window (BEW). During water experiments with identical BEW geometry, the streamlines were visualized by illuminating the flow, which was seeded with the particles, with the laser light. This approach did not provide quantitative information about the spatial flow structures inside the target, which is necessary for numerical model validation. Taking into account that widely used models do not correctly describe the heat transfer in liquid metal flows, a reliable prediction of the velocity flow field is crucial for any further considerations.

Therefore the verification of numerical models and testing of various BEW configurations were initiated in order to ensure the reliability of approaches and procedures, which are used for development of new targets. Since for model validation information about flow characteristics is needed in as large spatial region as possible, 2D PIV was chosen as appropriate experimental technique.

1. Turbulence Modelling and Combined Filtering

Most of the up-to-date turbulence models implemented in various commercial codes predict well the average velocity field. They can ensure good evaluation of integral or hydraulic characteristics, but it might be insufficient for the necessary in-depth description of local turbulent heat and mass transport properties.

In numerous publications it became obvious that RANS turbulence models predict turbulence characteristics incorrectly compared to experiment and LES models [2-3]. Mentioned examples do not mean that RANS approach gives incorrect results in general, but it is clear that long time averaging can lead to smearing out of local flow properties. Therefore, this is a motivation for using more advanced computational methods such as LES.

Imperfection of RANS approach comes from its definition – all quantities are modeled in the form of a Reynolds decomposition $u = \bar{u} + u'$, with u denoting the instantaneous velocity, $\bar{u}$ – the time averaged velocity, u' – the velocity fluctuation around the mean. Small scale fluctuations modeled with this approach, therefore influence of this part of turbulence spectrum obey certain assumptions. On the other hand – LES models can resolve large-scale turbulent structures up to a given cut-off scale due to the space-filtering. Quantity decomposition into a space-filtered value and a fluctuating component can be described by $u = \hat{u} + \tilde{u}$, where $\hat{u}$ denotes the filtered component and $\tilde{u}$ – the sub-grid scale component. Thus, the smallest resolvable turbulent scales are proportional to the finite mesh element size.

A number of numerical calculations using RANS approach – standard k-ε and Shear Stress Turbulence (SST) model – and LES – Smagorinsky and differential model [4] – were carried out with the OpenFoam code. Meshes used for RANS contained 1.2 million elements, for LES calculations – 3 million elements.

2. Measurements

Although various techniques that allow measurements of local velocity in the liquid metal flow [5] can be found in literature, an experiment with a plexiglas model and water as a working fluid was chosen due to its simplicity, price, availability for using PIV method and possibility of exchanging geometrical configurations. Furthermore, better space and time resolution could not be obtained in the liquid metal flow even with most up-to-date sophisticated techniques like CIFT [6] and neutron tomography.

The Reynolds numbers for the present experiment covers the range $1.7 \cdot 10^4$ to $1.1 \cdot 10^5$. For liquid metal (for instance LBE), these values would be an order of magnitude higher. But, since the flow is developed, there is no qualitative change in distributions of the velocity and turbulent properties with a variation of the flow rate. This leads to a conclusion, that time-averaged velocity and turbulent characteristics measured in water flows can be appropriately scaled to the representative quantities for the liquid metal flows.

3. Experimental Setup

In the experimental setup the target window is made of plexiglas, which is transparent, therefore allows illuminating the seeding particles in the water flow and taking pictures of them with a camera (Figure 1). The riser tube and jet guides (plates) are made of metal and cause reflections, which reduce the available field of view for camera and a number of

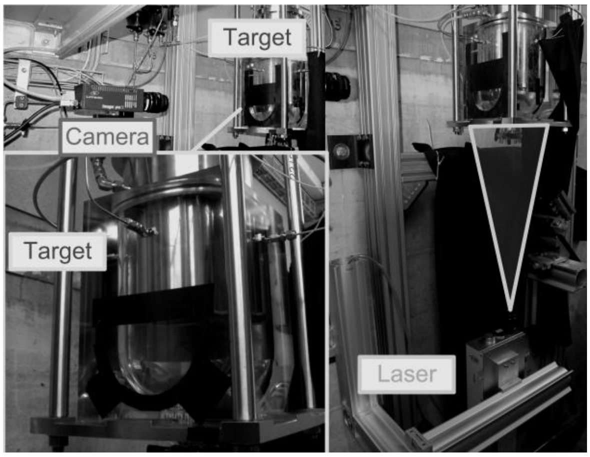

Fig. 1. Photo of PIV experimental setup. The laser is placed under the target head, which is made of Plexiglas. Camera takes pictures in vertical cross section

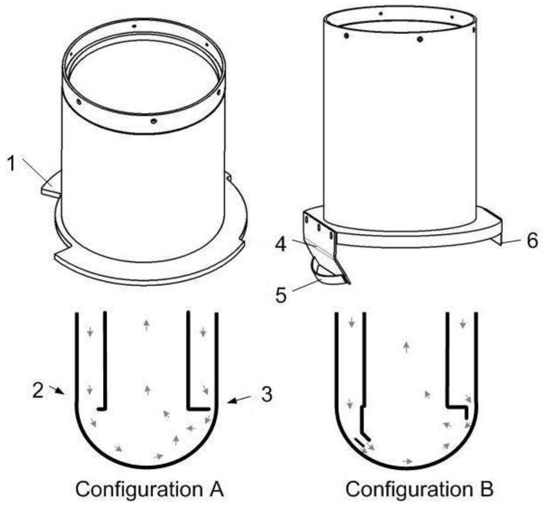

Fig. 2. Riser end configurations A and B: 1 – riser skirt; 2 - main jet opening; 3 – additional jet opening; 4 – main jet guide; 5 – turbulence promoter; 6 – additional jet guide

obtained data points. The spherical target window surface also leads to significant image distortions and we found several zones in the field-of-view where no clear signal is obtained.

From several initial configurations, which were examined by using RANS numerical model, the final reference geometry was chosen (A1 configuration). The configuration consists of ring with 60° gap (Figure 2), which is welded to the riser end.

Even though this geometry does not meet the criteria for real liquid metal targets, as the incoming flow is relatively far away from the spherical surface, it was extensively investigated. This configuration is relatively simple in construction and ensures a large field of view for the measurements. Modification of this geometry was also tested (configuration A2), with additional smaller gap on opposite side, but it was not optimized, and the flow through this gap was very small. The mean velocity and turbulence characteristics were not influenced compared with configuration A1. But this configuration was used to check symmetry (whether rotation of measurement plane by 30° in opposite directions gives same results).

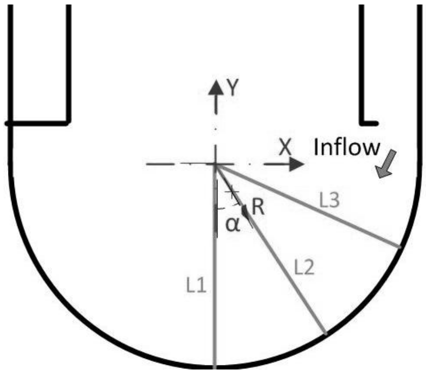

Fig. 3. Lines used for comparison of results. Lines are located in symmetry plane (Figure 2, bottom), largest inflows for all configurations on the right side. Angle α for L1 – 0°, for L2 – 37°, for L3 – 63°

In order to make a first step toward a development of the one pump target system, additional measurements were made for geometry with a longer riser, therefore the flow conditioners are closer to the spherical surface. In this geometry (configuration B1, an author of the idea Platnieks (IPUL)), the flow conditioners are welded to the rings, so that the flow is guided along the spherical surface of the target (similarly as in MEGAPIE). A smaller gap is on opposite side with the smaller plate. Platnieks stated that a flow obstacle, introduced in such system, can intensify the turbulent fluctuations, and also surface cooling effect. This idea leaded to modification of the configuration B1 – the configuration B2 with a semicircle obstacle (turbulence promoter) welded to the large plate.

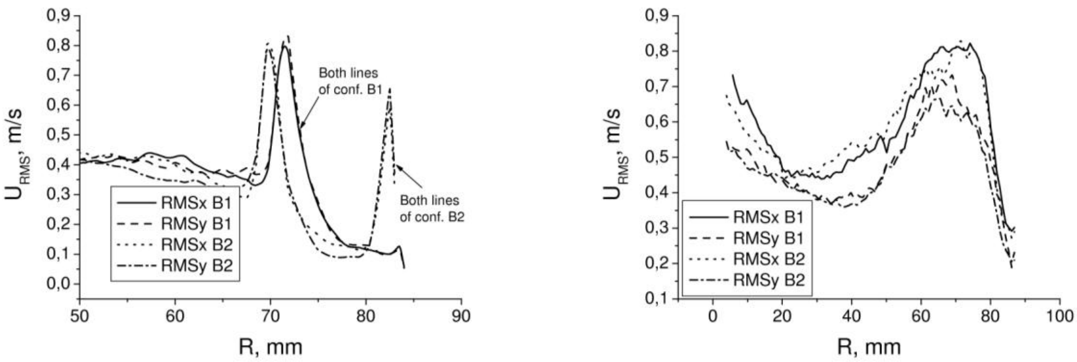

Fig. 4. RMS velocity profiles along lines L2 (left) and L1 (right). On line L2 zoomed zone near wall is shown – from 50 to 88 mm, where 0 corresponds to the centre of sphere. Full range shown on line L1 (0 to 88 mm)

4. Results

4.1. Influence of Turbulence Promoter

Obstacles immersed in the flow can intensify the turbulence production and therefore the turbulent heat transfer which is desirable for an enhanced window cooling. The velocity on the opposite sides of the obstacle has to be different either by a value, or by a direction (different substances also can lead to this effect, but it is not topical here). The obstacle in B2 divides the gap into two parts with area ratio of ~2, the smaller area is near the wall.

There are no significant differences in mean velocity distributions within the measurement error (up to 0.7 m/s in certain regions). Figure 3 shows locations chosen for comparison of the velocity fields. Profiles of the RMS fluctuations of the velocity show a local maximum, which appears near the spherical wall immediately after the turbulence promoter (Figure 4 left). Though, nearness of wall and edge of field-of-view oblige to view this result with caution. Additional close-up measurement should make it clear.

No differences between configuration B1 and B2 results are present in profiles of the RMS fluctuations of the velocity along line L1 (Figure 4, right), which can be explained with significant turbulence energy dissipation near the wall. Indeed, an obstacle in the flow can intensify turbulence, but in this case captured large-scales turbulent structures are already dissipated (after several centimetres) and does not reach the middle of the spherical surface.

4.2. Validation of Turbulence Models

In order to compare PIV and computational results obtained from different models, profiles of the x-velocity component and kinetic energy along line L1 are shown in Figure 5.

Looking into details, a tendency is visible, that in LES and SST k-ω models velocity *x*

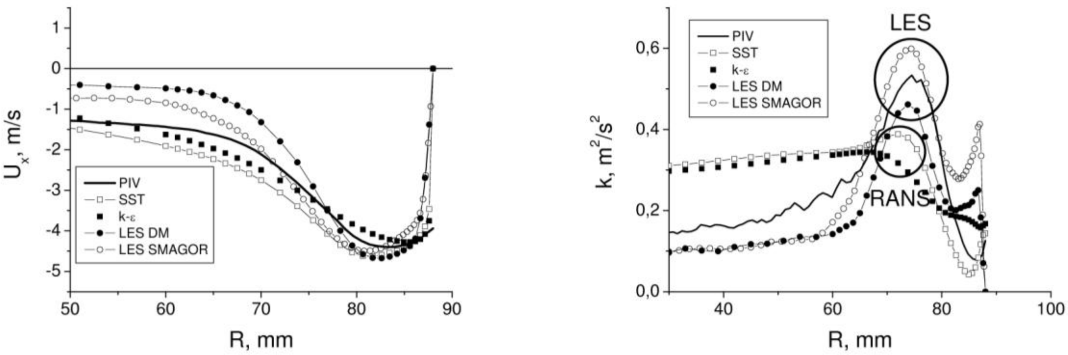

Fig. 5. Profiles of the x-velocity component (left) and turbulence kinetic energy (right) along the line L1 obtained with PIV and the different turbulent models

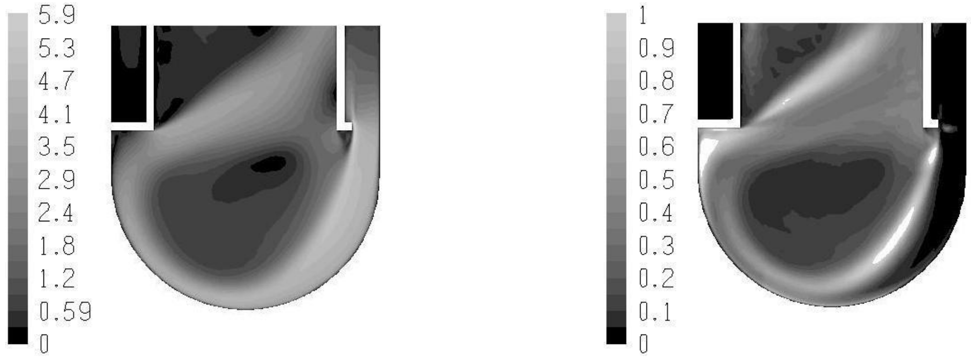

Fig. 6. Mean velocity contour (m/s, left) and turbulence kinetic energy (m^2/s^2 right) obtained in LES calculation in configuration A1 for *5 l/s* flow rate

component maximal value is further from wall, than in experiment and k-ε model data. However, it is possibly connected not with some characteristics of the model, but with incorrectly determined radial coordinate in the experiment.

All models describe the mean velocity field correctly. But in estimated turbulent characteristics similar tendencies as in references [2-3] have been shown up. Both standard and two-parameter models (*k-ε* and SST) predict relatively low turbulence kinetic energy in the zone along inner edge of the dominant flow direction (Figure 6, left). But in both models a local maximum can be more pronouncedly distinguished in case of SST model (Figure 5, right). Turbulence kinetic energy values estimated by RANS approach are more than 30% lower comparing to LES and PIV data. Other lack of RANS models is overrated turbulence kinetic energy in the center of the forming vortex. On the other hand – LES model results correspond qualitatively and quantitatively well to experimental data.

Figure 5 also shows that the turbulence kinetic energy is increased near the wall with exception of the prediction with the *k-ε* model. This observation can be explained with strong viscous stresses caused by high velocity gradient. The incorrect result of the k by *k-ε* model can be probably associated with inaccurate description of a boundary layer (values of y^+ near the wall are out of recommended range) and the overrated effect of a friction near the wall.

Comparing the 2D velocity field, some differences are also visible for the mean velocity, where the maximum is placed further away from the wall. In Figure 7 it is visible that in the PIV results, the velocity distribution near the inflow is more uniform compared with he CFD results. The LES model (Figure 6, left) estimates more precisely the location of mean flow vortex center than the RANS model (not shown here), very similar to PIV result.

For the turbulence kinetic energy distribution, several important qualitative differences are found (Figures 6, right, and 7, right). For the LES results , all the same characteristics as in

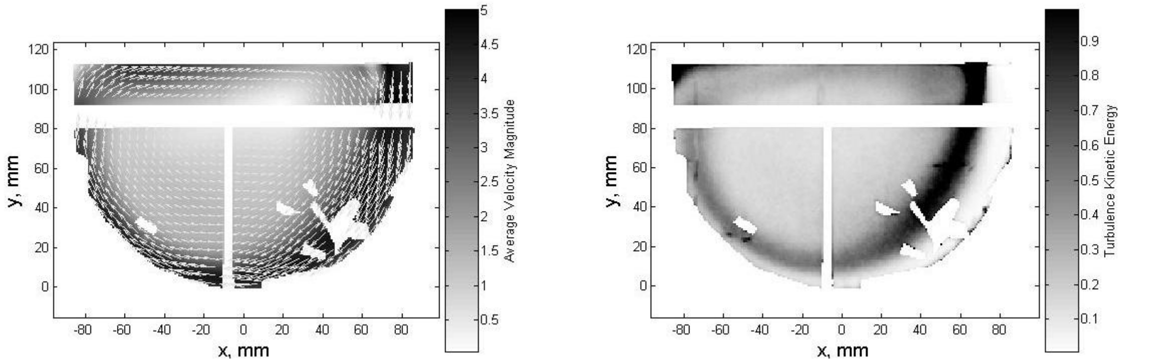

Fig. 7. Mean velocity map (left) and turbulence energy (right) obtained with PIV in conf. A1, *5 l/s* flow rate. White regions correspond to areas with low data quality

experimental data are visible, which cannot be concluded for the RANS results, where turbulence kinetic energy is underestimated on the inner edge of the mean flow and overrated in the vortex center. RANS also underestimates velocity pulsations in the corner on the opposite side to the inflow section, whereas in the LES results the local maximum is present, but the peak value is *~20%* lower. None of models predicts the local velocity peak in the zone near the inflow as presented for the experimental data. In order to analyze this region more carefully, data extracted along line L3 was done (not shown here).

For the velocity distributions a tendency was shown, that in all results of calculations velocity maximum is shifted further away from the wall. This is probably associated with the finite length of a computation domain – constant velocity boundary condition is applied at the inlet. As a result the flow profile is forming along shorter path than in reality. It is also visible, that none of numerical models estimates turbulence energy precise enough.

Conclusions

During this project successful and extensive measurements and computations were carried out where significant experience was gained in conducting PIV experiments for constrained curved geometries. The knowledge acquired produces necessary reference basis for further development of the new targets in the future. It was proven that obstacle in the flow can intensify turbulence, but optimization is needed.

During calculation phase of this project, RANS and LES results in using OpenFoam were compared. Both approaches showed good performance in estimating the mean flow field, with small differences, mainly connected with the finite length of the computational domain. For the turbulent kinetic energy field, the RANS based calculations are considerably worse compared with the LES calculations – few qualitative differences are present, however turbulence energy field estimated by LES model is in better agreement with experimental data.

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