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Turbulence Model Affect on Heat Exchange Characteristics Through the Beam Window for European Spallation Source

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Abstract

The aim of this paper is to compare k-ω Shear Stress Transport (SST) and Large Eddy Simulation (LES) turbulence model application affect on numerical computation of flow pattern and heat exchange characteristics through the neutron beam window region for European Spallation Source (ESS) setup model. Transient hydrodynamic (HD) and thermal calculations (TC) with appropriate heat sources are performed using both turbulence models and typical differences in flow and thermal patterns are discussed.

Introduction

Nowadays, the great varieties of engineer tasks are concerned with the heat transfer problems, partially, on heat exchange intensification. For instance, in the context of the ESS Project [1] the concept of the liquid metal target, where liquid metal is transferred through the active zone using MHD pump, is applied.

Experiments with mercury as liquid metal were performed in the Institute of Physics University of Latvia (IPUL). These experiments [2] were aimed on determination of distribution of fluid to wall heat transfer coefficient α_{FW} at the window surface.

On the basis of this experimental data the verification of numerical computation approach for flow pattern and heat transfer was performed. These studies included examination and comparison of turbulence models, performing calculations using RANS and URANS two parameter k-ω SST model and LES that in another applications with similar vortex structure (e.g. for metal melting furnaces [3]) give good correlation with experimentally estimated turbulent flow and heat exchange characteristics.

1. Turbulence Models

Turbulent flows contain eddies with a wide range of length and time scales that interact in a dynamically complex way. In LES it is assumed that the small eddies are nearly isotropic, on the other hand, large eddies behaviour and axis direction is dedicated by the geometry, boundary conditions and body forces. The large scale turbulent flow is computed directly with time-dependent simulation and the influence of the small scales is taken into account by appropriate subgrid-scale models.

Much simplified and modest for computer recourses way for numerical treatment of turbulence is the Reynolds-averaged Navier-Stokes concept, where attention is focused on the mean flow and the effects of turbulence on mean flow properties. Time averaging of flow equations is performed for typical Δt which is large relative to the turbulent fluctuations, but small relative to the time scale to which the equations are solved. Most prominent two-equation model in this area is k-ω SST model [4] that gives a highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients by the inclusion of transport effects into the formulation of the eddy-viscosity that corresponds for energy dissipation on all scale “a priori isotropic” eddies. The aim of this research is to investigate these different model application feasibility for ESS heat transfer problem solution.

2. Experimental Setup

A full scale mock-up experiment for liquid metal target was installed at the large mercury loop in the IPUL. The experimental setup [2] consisted of two coaxial cylinders and hemisphere (Fig. 2). In order to study the wall to liquid heat transfer, a Heat Emitting Temperature Sensing Surface (HETSS [5]) was developed and used to measure the temperature difference between the mercury and the wall under different geometric and flow conditions.

The HETSS detector was attached to the inner surface of hemisphere and as the hemisphere had rotation freedom around cylinder axis it was able to measure heat transfer coefficient distribution in different directions along hemisphere (Fig. 1).

$g = 2\ cm$
$h = 50\ cm$
$w = 0.5\ cm$
$R_{in} = 10\ cm$
$R_{out} = 20\ cm$

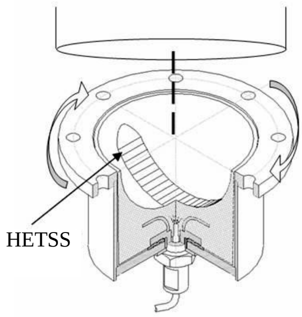


Fig. 1. Revolvable hemisphere and HETSS detector

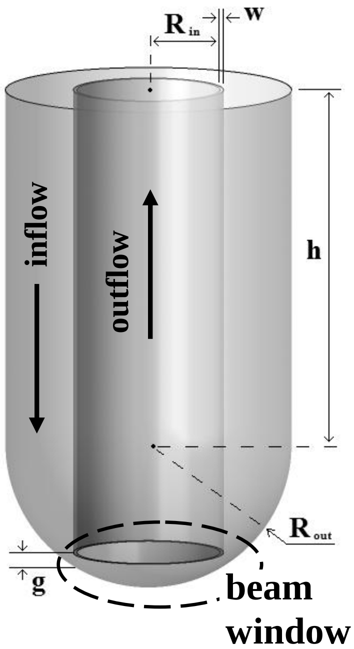


Fig. 2. Geometry of axially symmetric setup

3. Numerical Model

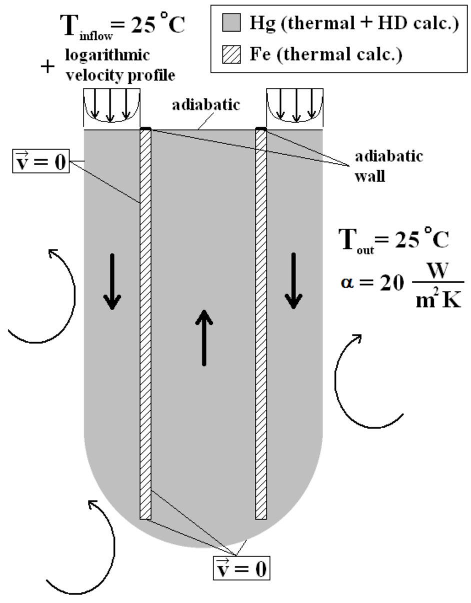
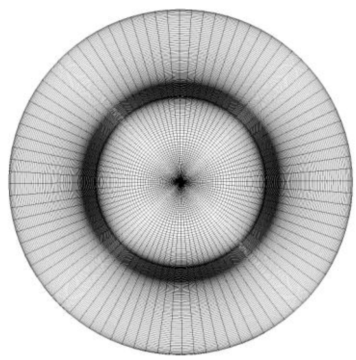
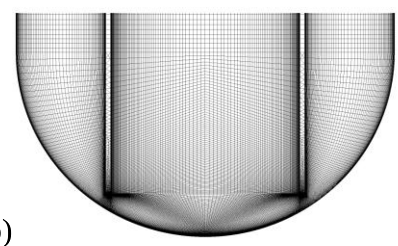


Fig. 3. Model boundary conditions



a)



b)

Fig. 4. Model mesh on hemisphere a) and on axial cross-section b)

For HD calculation non buoyant mercury was used as model liquid with total inflow of 3.6 *l/s* and appropriate turbulent velocity profile as inlet boundary condition (Fig. 3). As usually, wall affect on flow was described with no-slip condition ($\vec{v} = 0\, m/s$).

TC were performed both for liquid mercury and solid steel walls. At surfaces common for both material domains temperature values were automatically coupled. For TC it was considered that inflow Hg is at a constant temperature of $25^{\circ}C$. At outer cylinder walls and hemisphere surface convection BC was applied considering $T_{out} = 25^{\circ}C$ and wall to atmosphere surface heat exchange coefficient $\alpha_{WA} = 20\ W/(m^2K)$.

ANSYS/CFX commercial software was used to perform calculations on structured mesh (Fig. 4) with $2.5 \cdot 10^6$ elements for LES calculation and $0.8 \cdot 10^6$ elements for k-ω SST. 7 kernels were involved in LES calculation and 1 *s* of flow took 24 hours of physical time. Transient calculations were performed for (6 + 20) *s* taking as initial condition SST steady state calculation results and excluding from further time averaging transitional flow for the first 6 *s*.

4. Thermal Source

As a result of collision between high energy protons and heavy metal atoms apart from intensive pulses of neutrons great amounts of thermal energy in window beam adjoining volume are emitted. Thermal energy source density $q\ \left[W/m^3\right]$ distribution was qualitatively adopted from [6]. For model calculation *q* was considered exponentially vanishing along symmetry axis distancing from beam window (Fig. 5). In radial cross-section it was considered Gaussian shaped (Fig. 6). Applying adjusted expression for thermal source density distribution

$$q(x,y,z) = a \cdot \left(e^{-\left(\frac{x^2+z^2}{b}\right)} + e^{-10(y+c)}\right) \quad \left[W/m^3\right], \tag{1.1}$$

the total power of 0.3 *MW* in considered volume of 0.077 m^3 was obtained by $a = 10^7$, $b = 0.0128$ and $c = 0.2$.

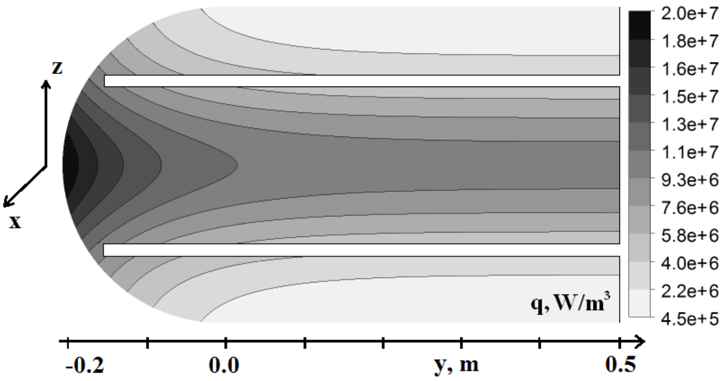


Fig. 5. *q* distribution on axial cross-section

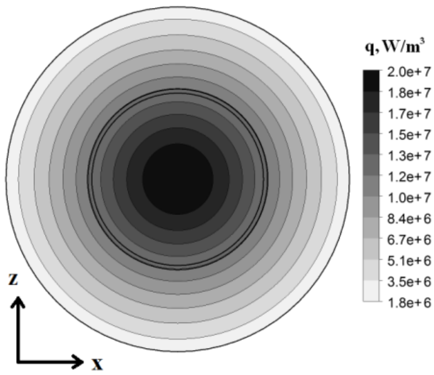


Fig. 6. *q* distribution in 1 *mm* from hemisphere

5. Results

The main object of interest is turbulence model affect on flow and thermal pattern near the beam window (hemisphere). In this region most remarkable overheating is expected by two reasons: thermal energy source has the intensity maximum (1.1) and no-slip condition near the wall minimizes the flow intensity and reduces convective heat transfer contribution.

Time averaged results for flow pattern and temperature distribution are presented on axial cross-sections (Fig. 9) and in 1 *mm* from hemisphere (Fig. 10). Despite that both turbulence models show good agreement in velocity fields with flow velocity maximum corresponding to the gap and axial jet and characteristic vortex structures (Fig. 7, Fig. 8, a) and Fig. 9, a)), still turbulence kinetic energy (k-energy) fields differs significantly both for qualitative and quantitative scenes. The difference in k-energy distribution clearly obtainable from cross-sectional plots (Fig. 8, b)) and absolute scale discrepancy reaches the factor of 10 in 1 *mm* from hemisphere (Fig. 9, b)).

According to assumption that high k-energy in wall region reduces the thickness of laminar sub-layer, for which in heat exchange process dominates heat conduction, the increase of fluid to wall heat transfer coefficient α_{FW} at the surface and more intensive heat exchange through the beam window is expected. More intensive flow to wall heat transfer leads to greater thermal losses that should decrease average temperature values encountered in hemisphere volume.

Despite that characteristic values for wall to atmosphere heat exchange coefficient $\alpha_{WA} = 20\ W/(m^2K)$, inflow and atmosphere temperatures $T_{inflow} = T_{out} = 25°C$ were adopted from experimental data [5], thermal energy loss through walls ($\approx 10^{-4}$ *MW*) is negligible in comparison to convective thermal energy loss through the outlet ($\approx 0.3\ MW \approx q$). For such parameter choice walls are nearly adiabatic and turbulence model affect on intensification of heat transfer through beam window has the order of error caused by mesh discrepancies. Performance and result analysis of numerical experiment with comparable heat loss through walls and outlet forms the further plans for research.

Still, greater maximal temperature values on hemisphere (Fig. 10, c) for LES calculation lead to greater heat flux through hemisphere and more intensive cooling of beam window region.

The flow near beam window could be treated as radial contra oriented jets parallel the hemisphere colliding near the setup axis (Fig. 8). As the result of collision the flow is oriented away from setup axis and at this moment four eddies are formed. Due to axial symmetry initial jet orientation is equally probable that causes such four eddy system instability with rotation around setup axis and reorganization. Such instabilities are strongly marked in LES calculation and despite low velocity values lead to fluid admixture and temperature drop on axis (Fig. 10, c).

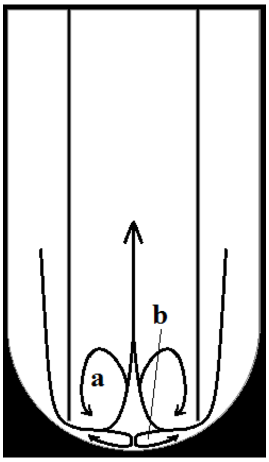


Fig. 7. Time averaged typical vortex structure

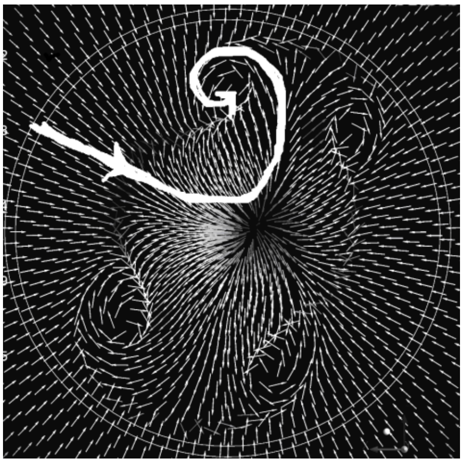


Fig. 8. Velocity field at particular time moment for SST calculation

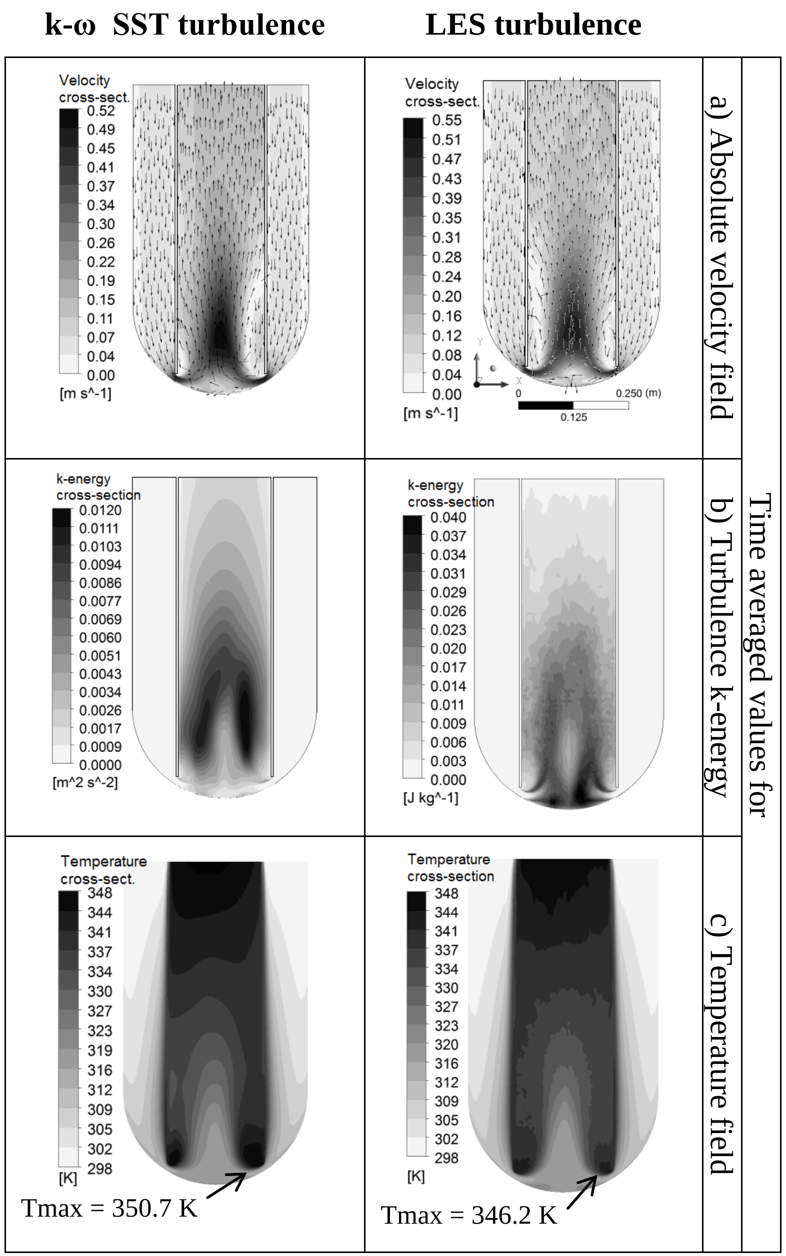


Fig. 9. Axial cross sections

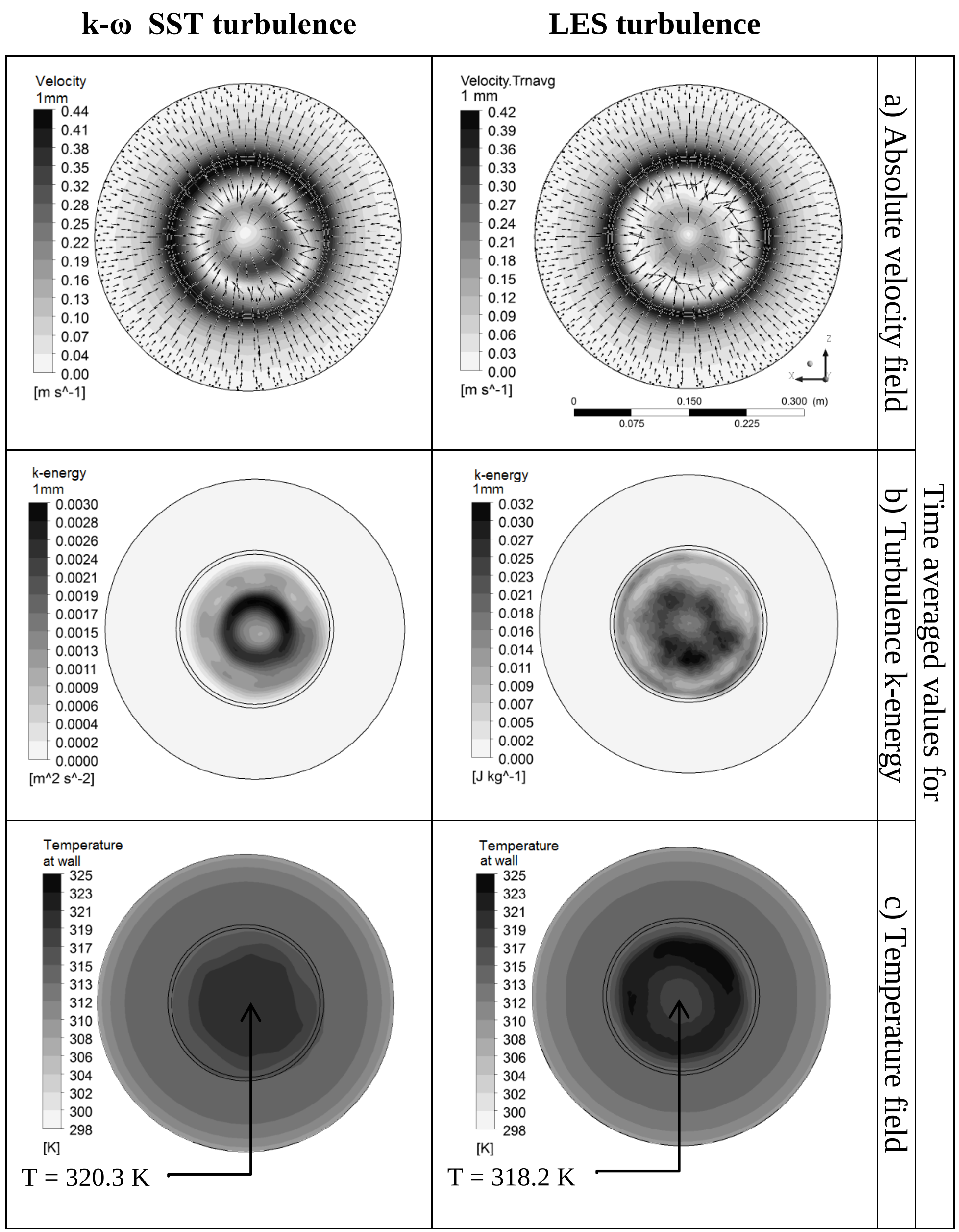


Fig. 10. Beam window region

However, turbulence kinetic energy is only one of various parameters that affect temperature distribution. Overheating also is expected in regions with low flow intensity such as vortex centers (Fig. 7, a) where contribution of convective heat transfer is damped. In this case, greater velocity turbulent pulsation values encourage fluid admixture and intensify heat leakage from overheated regions. Greater k-energy for LES leads to less maximal and average temperature values obtained in vortex centers (Fig. 9, c).

For LES calculation (T_{Hg}^{ave} = 315.6 *K*) time averaged mercury temperature in whole domain that corresponds for quasi thermal steady state is less than for SST (T_{Hg}^{ave} = 315.1 *K*), however, such difference lies within mesh error.

Greater kinetic energy of turbulence for LES model calculation ensures greater effective heat conduction in the whole mercury domain. Ensuring significant thermal losses through walls, less average temperature that corresponds for quasi thermal steady state is expected for LES calculation.

Conclusions

For current inflow and outer temperature values, thermal source total power and wall to atmosphere heat exchange coefficient the effect of turbulence model on temperature distribution in beam window region has the order of calculation error. However, typical temperature field discrepancies caused by difference in model calculated k-energy patterns are notable. Presumably, turbulence model effect on temperature field becomes strongly marked by ensuring greater heat flux from walls to the outside. Greater turbulent velocity pulsations for LES turbulence model intensify domain cooling and heat exchange in fluid and decrease average mercury temperature. Numerical experiment applying comparable thermal losses through walls and outlet forms the further plans for assumption verification.

References

[1] Clausen, K. N.: *ESS – The European Spallation Source*. ICANS-XVI 16th Meeting of the International Collaboration on Advanced Neutron Sources. May 12 – 15, 2003. Düsseldorf-Neuss, Germany.

[2] Lielausis, O., Dementjev, S., Bucenieks, I., Platacis, E., Platnieks. I.: *Riga experience and capacity in spallation target related investigations*. 4th International Conference "MHD at Dawn of the 3rd Millenium", France, September 18-22, Vol. 2, 2000, pp. 365-370.

[3] Kirpo, M., Jakovics, A., Baake, E., Nacke, B.: *Analysis of experimental and simulation data for the liquid metal flow in a cylindrical vessel* . Magnetohydrodynamics, Vol. 43, 2007, No. 2, pp. 161 – 172.

[4] . Versteeg, H. K., Malalasekera, W.: *An Introduction to computational fluid dynamics*. Pearson Education Limited, 2007.

[5] Platnieks. I.: *Heat transfer experiments using HETSS*. 4th MEGAPIE Coordination Meeting (WP X4-X6), Brasimone, 5 oktober 2000. ENEA Centro di Ricerche Brasimone, Italy.

[6] Final Report of the Eurisol Design Study. France, September 2009, p. 22, p. 47.

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