CFD Study of the Active Part of the HYPER LBE Spallation Target System

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1. Introduction

In an accelerator driven system (ADS), a high-energy proton beam impinges on a heavy metal target to produce spallation neutrons that are multiplied in a sub-critical blanket. Therefore, the spallation target is one of the most important units of an ADS. A beam power of 15~25 MW is required for an operation of the HYPER system [1]. But, the design of a 20 MW spallation target is very challenging because more than 60% of a beam power is deposited as heat in a small volume of a target system.

LBE is preferred as the target material due to its high neutron production rate, effective heat removal, low melting point and vapor pressure, low neutron absorption and good radiation damage properties. In addition, it can be used simultaneously as a reactor coolant. Single hemi-spherical beam window is considered for the HYPER target.

The beam window is a thin physical barrier to separate the vacuum space from the LBE. It is exposed to high thermal and irradiation loads, which affect its life time. The integrity of the beam window is crucial for a safe operation of the HYPER, for preventing the penetration of the radioactive spallation products into the accelerator island. Therefore, a sufficient cooling capability of the beam window is one of the key issues of the target design.

In the previous study, a series of parametric thermal and mechanical studies were made for the optimization of the HYPER target [2]. The optimized target has a 0.2 cm thick beam window with a diameter of 35 cm. Also, a 30 cm wide proton beam with a uniform beam distribution should be adopted for the spallation target of the HYPER. A dual injection tube is adopted to economize the LBE flow in the primary system.

This paper presents the numerical studies on the optimized spallation target system. Several advanced turbulence models with different grid structures are investigated by using a commercial computational fluid dynamics (CFD) code CFX 5.7.1.

2. Description of Target System

The active part of the HYPER target is shown in Figure 1. A cylindrical beam tube with a hemi-spherical beam window is adopted for the target. The beam window thickness and the beam window diameter are 35 cm and 0.2 cm, respectively. A 30 cm wide proton beam with a uniform beam distribution should be adopted for the spallation target of the HYPER. The target channel diameter is set at 66 cm to protect the fuel assemblies from radiation damage caused by the high-energy proton beam, and to best couple the reactor to the spallation neutron source. The energetic proton beam penetrates the beam window and impinges on the upward flowing LBE. The temperature of the LBE entering the target channel is 340 °C, which is the same as that of the core inlet. A duel injection tube is placed at the inlet of the target channel in order to economize the LBE flow in the primary system and to reduce the possibility of a thermal striping in the upper plenum of the reactor core. The dimensions of the tube and the injection velocities were optimized by parametric studies [3].

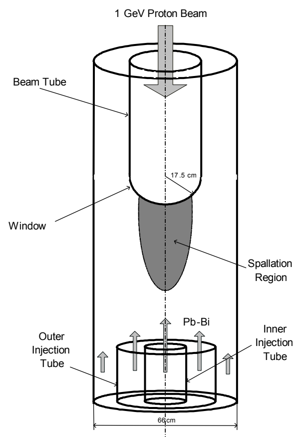

Figure 1. Active part of the HYPER target.

3. Numerical Analysis and Results

Heat generation inside the beam window and LBE is calculated by using LCS 2.7 [4] and the calculation result is used for the thermal hydraulic calculations as a volumetric heat source. The applied beam current is 19.6 mA. The heat deposition outside the beam radius is negligibly small and is thus neglected for the CFD calculations.

The axial temperature distribution of the inner core, which is a mean value at the gap region and implemented into the wall boundary condition for the thermal hydraulic analyses of the target system, is calculated by using the MATRA-LMR code [5] which is developed for a liquid metal cooled fast reactor (LFR) core analysis.

Figure 2 shows the computational domain and boundary conditions for the CFX calculations. An axi-symmetrical two-dimensional computation domain was chosen due to the symmetric conditions. The inlet velocities (V1, V2, V3) are 1.8, 0.3, 0.01 m/s, respectively. Pressure boundary condition is used for the outlet.

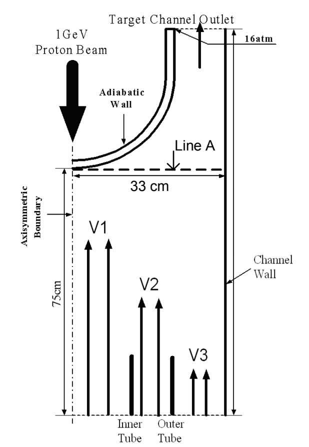

Figure 2. Computational domain and boundary conditions.

Five different advanced turbulence models were applied in this work. They are the standard k-ε model (k-ε), the k-ε model by the Renormalization Group of Princeton University (RNG k-ε), the sheer stress transport (SST) model, and two Reynolds stress models (LRR, SSG) for second moment closures.

Figure 3 shows the temperature distribution at an adiabatic wall surface of the beam window. There are discrepancies in the temperature at the adiabatic beam window surface. The k-ε model predicts the lowest window temperature among the investigated models, which is about 514℃ and the SST model predicts the highest window temperature among the investigated models, which is about 557℃. Various studies reported that the two equations turbulence models predict an anomalously large growth of the turbulent kinetic energy in stagnation point flows. In the case of the HYPER spallation target, there is a stagnation point flow at the centre of the wetted beam window surface.

The turbulent kinetic energy distributions in the target channel calculated by the two equations model (i.e. k-ε) and Reynolds stress model (i.e. SSG) are shown in Figure 4. The k-ε model generates a maximum turbulent kinetic energy at the centre of the wetted beam window surface, which is the stagnation flow region. What is more, the maximum value of the turbulent kinetic energy at the stagnation flow region predicted by the k-ε model is 859% higher than that of the SSG model. Such differences will directly affect the window temperature. The result clearly indicates that the selection of a turbulence model has to be made carefully.

4. Conclusion

Several advanced turbulence models with different grid structures were applied for CFD study of the active part of the HYPER target. The results reveal a significant impact of the turbulence model on the window temperature. Particularly, the k-ε model predicts the lowest window temperature among the five investigated turbulence models. It is concluded that the k-ε model does not properly represent the active part of the HYPER spallation target and experimental verifications are invaluable for the design of the HYPER target.

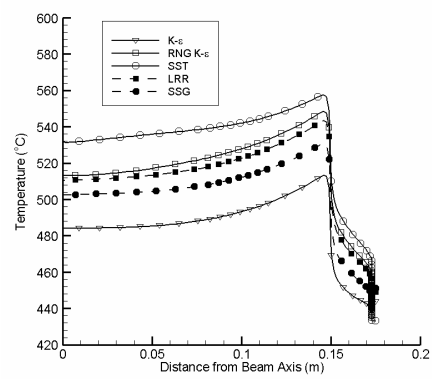

Figure 3. Temperature distribution at the adiabatic surface of the beam window

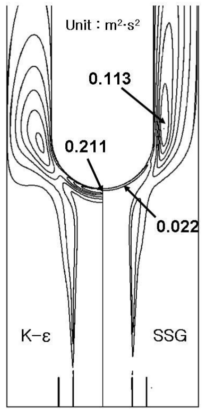

Figure 4. The turbulent kinetic energy distribution in the target channel

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