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Thermodynamic analysis and simulation for gas baffle entrance collimator of EAST-NBI system based on thermo-fluid coupled method

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Abstract The world's first full Experimental Advanced Superconducting Tokamak (EAST) is designed with the auxiliary heating method of neutral beam injection (NBI) system. Beam collimators are arranged on both sides of the beam channel for absorbing the divergence beam during the beam transmission process in the EAST-NBI system. The gas baffle entrance collimator (GBEC) is a typical high-heat-flux component located at the entrance of gas baffle. An efficient and accurate analysis of its thermodynamic performance is of great significance to explore the working limit and to ensure safe operation of the system under a high-parameter steady-state condition. Based on the thermo-fluid coupled method, thermodynamic analysis and simulation of GBEC is performed to get the working states and corresponding operating limits at different beam extraction conditions. This study provides a theoretical guidance for the next step to achieve long pulse with high-power experimental operation and has an important reference to ensure the safe operation of the system.

Keywords Neutral beam injection · High-heat-flux component · Beam collimator · Thermo-fluid coupled method · Thermodynamic analysis

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1 Introduction

Neutral beam injection (NBI) is an important auxiliary heating method for Tokamak devices, with high heating efficiency and clear heating mechanism. Two sets of NBI system have been used in the Experimental Advanced Superconducting Tokamak (EAST) in China [1–4]. Plasma generated in the ion source has uniform ion density and space charge effect of particles, and the beam will continue to diverge during the process of beam transmission [5, 6]. To prevent instability of the system caused by the divergent beam bombardment to the main components inside the vacuum chamber, collimators to absorb the divergent beam are required for various components and arranged around the beam channel. Varieties of temperature measurement devices are arranged to get temperature profile and introduce working status of the ion source and the extraction system. The beam collimators around the beam channels of NBI system are mainly located at the ion source exit, the entrance of gas baffle (gas baffle entrance collimator, GBEC), and the entrance and outlet of deflection system. How to confirm the reliability of these heat transfer structures in design conditions is important for system safe operation.

The designs of high-heat-flux (HHF) components are optimized on the basis of thermo-fluid analysis. Considering the characteristics of different HHF components, several authors used the design-by-analysis approach with help of 3D computational fluid dynamic codes and achieved the components thermal hydraulic condition [7–9]. In the International Thermonuclear Experimental Reactor project (ITER), the supporting structures of plasma-facing components are designed on the basis of thermal hydraulic analysis [10, 11]. 3D thermal thermo-hydraulic analysis with the flows-solid coupling heat conduction model has been carried out for the cooling structure of EAST tungsten divertor, the water cooled ceramic breeder blanket for Chinese Fusion Engineering Test Reactor [12] and the typical HHF ion dump of EAST-NBI system [13].

In this paper, according to the engineering requirements and the structural design features of the GBEC in the EAST-NBI system, the thermo-fluid coupling analysis and 3D simulation of the beam collimator under different beam extraction parameters are presented. The results provide a theoretical guidance of operation ability for the components in the long-pulse quasi-steady-state experimental conditions.

2 GBEC of the EAST-NBI system

Figure 1 shows the GBEC of EAST-NBI system. It is located at the neutralizer outlet and upstream of the deflection magnet, between Cryopumps 1 and 3. A gas baffle is to form differential pressure distribution in the main vacuum chamber, so as to assure the beam transmission. The beam collimator uses the cooling tubes welded within the main structure and is suitable for assembling and disassembling of the NBI system. The collimator is composed of four plates (Fig. 1b). External frame is sized at 300 mm × 600 mm, while the internal cavity is sized at 150 mm × 470 mm. The two sizes can be properly adjusted by considering beam divergence of system. The oxygen-free copper plates of 50 mm thick are built with stainless steel tubes of Φ12.5 mm to flow cooling water. In order to measure the energy deposition on the GBEC with the water flow calorimetry (WFC) system [14], the SS tubes adopt in series structure with one inlet and one outlet. According to previous beam transmission theoretical research and experiment, the energy deposition value on the four target plates is about 2.33% of the total beam energy at the entrance of the gas baffle [15], and the beam intensity distribution of GBEC is shown in Fig. 2.

3 Numerical model of thermo-fluid coupled analysis of GBEC

In this paper, the structure model is simplified and assumed as follows:

(1) The fluid is a steady-state in-compressible flow with no heat source inside;
(2) Only the walls facing the beam are subjected to the bombardment of particle energy, and the natural convection and thermal radiation are neglected;
(3) The contact thermal resistance between the tube wall and the plate is considered.

Based on these assumptions, the governing equations for turbulence and convective heat transfer of GBEC can be established. Details of the equations and corresponding algorithm by the finite volume method can be found in Ref. [16]. Here, turbulent numerical simulation is carried out by adopting the standard k–ε two equation viscous model. For describing the flow in the near-wall region accurately, the wall function method is introduced [17].

Mesh quantity is a key factor affecting the calculation, and the GBEC is divided into four pieces: two side plates and the upper and down plates (Fig. 1b), which are calculated one by one. The grid of geometric structure is shown in Fig. 3. The Tgrid mesh type is used for the main body of plates and the cooling tube, and the Hexahedral mesh is adopted in the fluid region with encrypted boundary layer [18–20]. Through the grid independence verification, the grid number is about 1 million, which can meet the precision of calculation requirement.

According to the flow process of cooling water in Fig. 1b, the outlet parameters of former plate are equivalent to the inlet value of the next one, and so forth. The

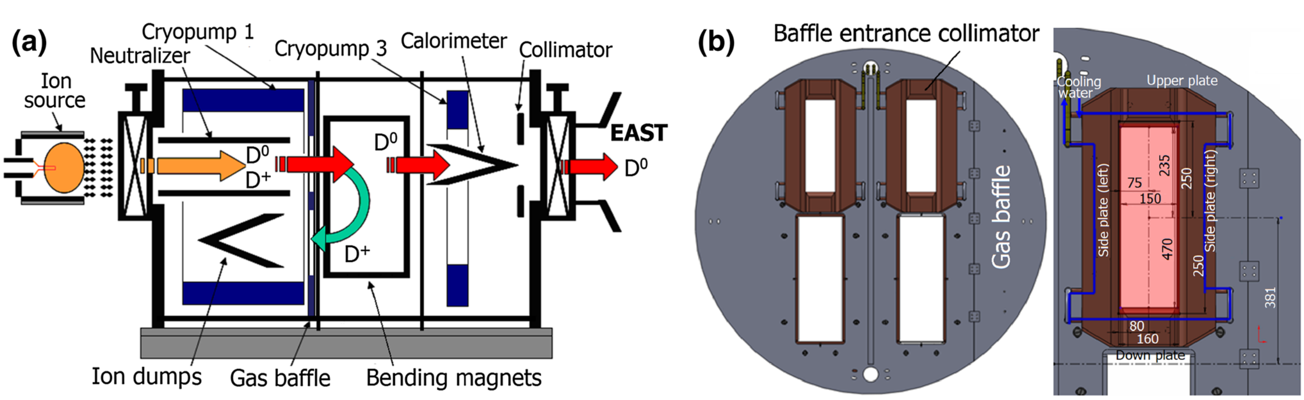

Fig. 1 (Color online) Structural schematics of the neutral beam injection of EAST (**a**) and the GBEC and cooling water tube arrangement (**b**)

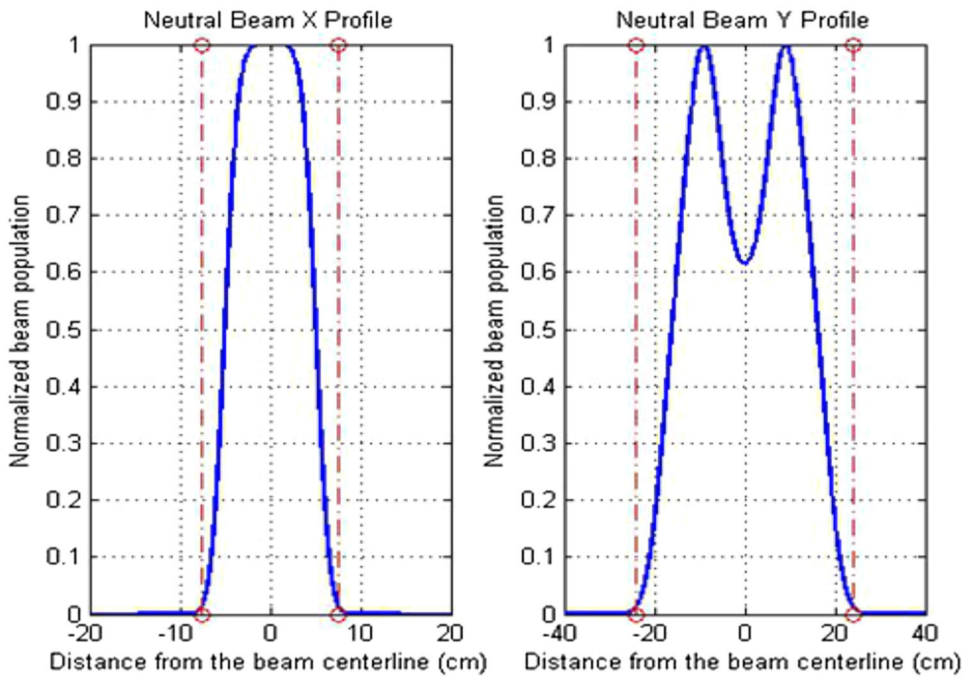

Fig. 2 Beam intensity distribution of GBEC

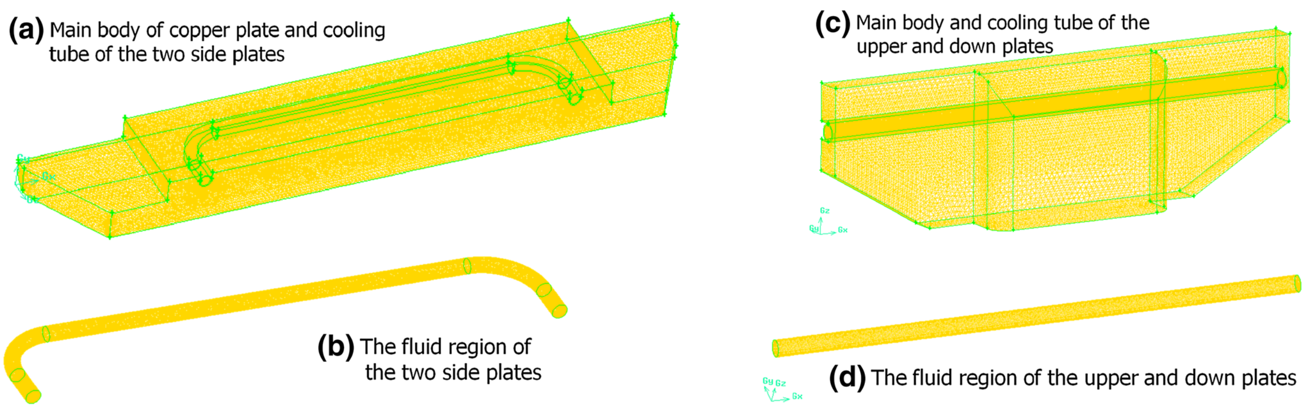

Fig. 3 (Color online) Grid distribution of GBEC

boundary conditions are: inlet pressure of the left plate, 0.7 MPa at 20 °C; outlet pressure of the right side plate, 0.1 MPa (the same as outlet boundary). The temperature-dependent physical parameters used in the calculation are listed in Table 1. During the simulation process, to keep the computational stability and avoid shaking of the residual curve, the under relaxation factors are set as 0.3 for pressure, 1.0 for density, 1.0 for body force, 0.5 for momentum, 0.3 for turbulent kinetic energy, 0.3 for turbulent dissipation rate and 0.5 for energy. The inlet boundary of cooling water is chosen to initialize the solution of flow field.

4 Results and discussion

In order to check whether the GBEC can meet the design requirements of the EAST-NBI in its long-pulse operation, heat transfer performance under different beam extraction conditions is numerically simulated. The beam extraction power, ΔP, is calculated by $\Delta P = IV$, where V is the high voltage loading for extraction, and I is the beam current extracted. The power depositions under high voltage of 50–80 kV and beam current of 33.5–67.9 A are shown in Table 2.

4.1 Steady-state analysis

Steady-state analysis is carried out to investigate whether the structure can be well operated under steady state,

Table 1 Material physical parameters[21]

Material physical parameter	Value (T denotes the temperature)
Specific heat of water (J kg^{-1} K^{-1})	$10608.87995 - 55.7362T + 0.15919T^2 - 1.49398 \times 10^{-4}T^3$
Density of water (kg m^{-3})	998.5
Thermal conductivity of water (W m^{-1} K^{-1})	$-0.51402 + 0.00532T - 3.35719 \times 10^{-6}T^2 - 6.22349 \times 10^{9}T^3$
Viscosity coefficient of water (kg m^{-1} s $^{-1}$)	0.001006
Specific heat of copper (J kg^{-1} K^{-1})	$372.54105 + 0.0409T + 4.2796 \times 10^{-5}T^2$
Density of copper (kg m^{-3})	8920
Thermal conductivity of copper (W m^{-1} K^{-1})	$421.47246 - 0.07225T + 2.64976 \times 10^{-6}T^2$
Specific heat of 316 SS (J kg^{-1} K^{-1})	502.48
Density of stainless 316 SS (kg m^{-3})	8030
Thermal conductivity of 316 SS (W m^{-1} K^{-1})	16.27

Table 2 Power deposition under different high voltages and beam currents

High voltage (kV)	Beam current (A)	Deposited power (MW)
50	33.5	0.039
60	44.1	0.062
70	55.6	0.090
80	67.9	0.126

i.e., the highest temperature on the plate surface does not exceed the softening temperature of the material. The temperature profile of steady-state analysis under different beam extraction conditions are shown in Fig. 4. The results show that the four plates of GBEC can bear different heat powers deposited. At beam extraction voltage of 80 kV, the deposited power on the GBEC is about 0.126 MW, corresponding maximum temperature of 694 K for the upper plate and 709 K for the down plate, much more than the soften temperature of oxygen-free copper (573 K). In this case, the thin-wall SS cooling tubes are likely to break down, and water to leak. At 70 kV, the maximum temperatures of the upper (613 K) and down plates (625 K) also exceeded the temperature limit, whereas the maximum temperatures of the side plates are 510 and 493 K at 80 kV, and 465 and 425 K at 70 kV. So, when the beam extraction

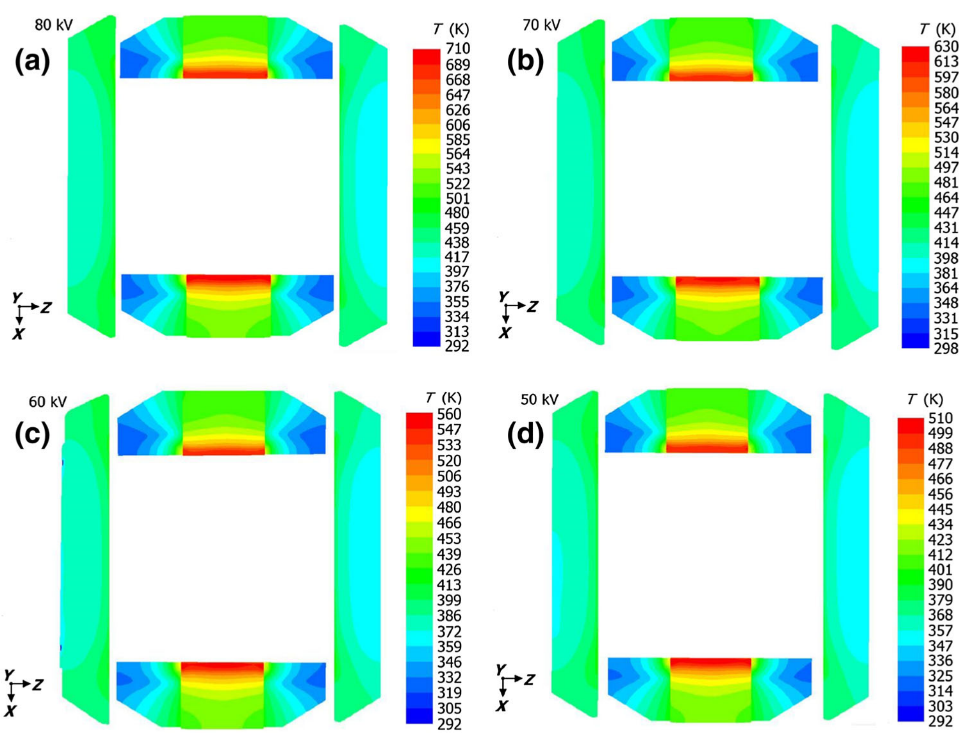

Fig. 4 (Color online) Steady-state temperature distribution of GBEC at the beam extraction voltage of 50–80 kV

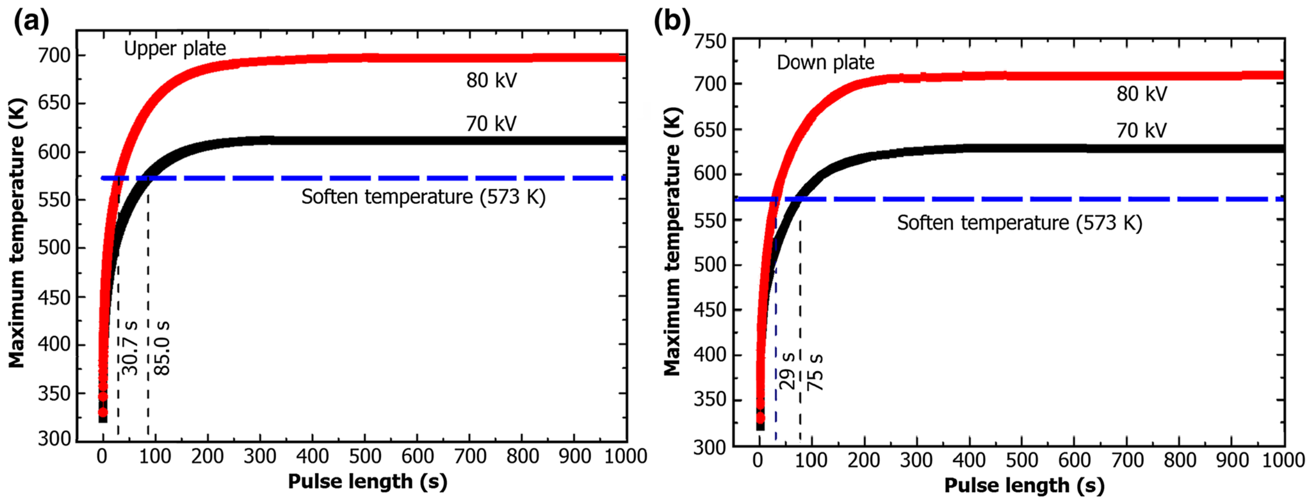

Fig. 5 (Color online) Maximum temperatures of the heat load surface of the upper and down plates at 70 and 80 kV, as a function of pulse duration

voltage is no more than 60 kV, the maximum temperature can be better controlled under the design limit of 573 K.

4.2 Transient analysis

According to the steady-state simulation results, the transient analysis is carried out for the upper and down plates at 70 and 80 kV to confirm the operation potential under 100 s pulse length. The maximum temperatures of the heat load surface of upper and down plates of GBEC at 70 and 80 kV versus the pulse length are shown in Fig. 5. According to the soften temperature of oxygen-free copper (573 K), at 80 kV, the longest working pulse length of the upper and down plates is only 30.7 and 29 s, respectively; while at 70 kV, they are 85 and 75 s, respectively. As a result, for the upper and down plates, the best working beam extraction voltage must less than 60 kV to reach the steady-state operation from the view of heat transfer. Without changing heat transfer structure of GBEC, for steady-state operation at beam extraction voltage of 70 and 80 kV, the main body material of the plates should be replaced by CuCrZr, the softening temperature of which is 723 K.

5 Conclusion

Based on the thermo-fluid coupled method and near-wall function treatment model, the thermodynamic analysis and simulation of the three-dimensional GBEC is established to get the working states at different beam extraction conditions. From the numerical simulation results, at beam extraction voltage is no more than 60 kV, the cooling structure can effectively achieve the temperature control to reach the steady-state operation of EAST-NBI system, but if the beam extraction voltage is over 60 kV, the material of the main body needs to be replaced by CuCrZr in order to fulfill the steady-state operation without changing cooling structure. This study provides a theoretical guidance for the next step to carry out long-pulse high-power quasi-steady-state experiments and has an important reference to ensure the safe operation of the system.

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