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ORIGINAL RESEARCH

Gas Flow in the Neutralization Region of EAST Neutral Beam Injector

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Abstract The gas flow in the neutralization region affects the neutralization efficiency as well as the beam transition efficiency of whole neutral beam injector, which will be applied as a high power auxiliary heating and non-inductive current driver system for the Experimental Advanced Superconducting Tokamak (EAST). The neutralization region of EAST neutral beam injector includes not only the gas cell neutralizer in traditional sense, but also part of the ion source downstream the electrode grid, the gate valve, and the transitional piping and fitting. The gas flow in this neutralization region has been modeled and researched using an adjusted Direct Simulation Monte Carlo code to understand the formation mechanism of gas target thickness, which determines the neutralization efficiency. This paper presents the steady-state, viscous and transition region flowfields, the gas density distribution and the various centerline profiles including Knudsen number, temperature, pressure and axial velocity by injected the deuterium gas from the arc chamber and neutralizer, respectively. The target thickness in the neutralization region as a function of gas inlet quantity is also given in the absence of beam for future operation of EAST neutral beam injector.

Keywords Transitional gas modeling · Gas cell neutralizer · Neutral beam injector · EAST · Direct Simulation Monte Carlo

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Introduction

A neutral beam injection (NBI) system is to be used as a high power auxiliary heating and non-inductive current driver system for the Experimental Advanced Superconducting Tokamak (EAST). Thus, the EAST-NBI system is very important for accomplishing the scientific mission of EAST project [1]. The EAST-NBI system comprises two identical injectors, and the major design parameters of each one were listed in Table 1 [2]. The neutralization is essential since only neutral particles can cross the strong magnetic field and reach the plasma region of EAST, so the neutralization efficiency is a significant parameter of EAST-NBI system. The sketch of the neutral beam injector for EAST is revealed in Fig. 1. In general, the energetic ion neutralization is achieved by charge exchange collision with target gas before separating the residual ions from the beam. The neutralization efficiency depends on target thickness π, also known as target gas linear density in neutralization region [3]. For EAST injector, the neutralization region (i.e., the area in the green dashed frame in Fig. 1) includes part of the ion source from the last electrode grid to the end, the cavity of the gate valve, the whole neutralizer, and the transitional piping and fitting. Note that, in the area from the end of neutralizer to bending magnet, the gas density is too small to neglect its contribution to the target thickness.

EAST neutral beam injector is based on positive ion source, whose neutralization efficiency increases with target thickness and tends to saturation gradually [4]. Generally, the optimum target thickness π_{opt} is the value required to achieve 95 % of the maximum neutralization efficiency, and the π_{opt} varies with different beam species and beam energy due to the collision cross sections [5]. The formation of target thickness is defined by the gas sources and geometry of the neutralization region. Hence,

Table 1 The parameters of EAST neutral beam injector

Parameter name	Quantity
Number of ion source	2
Angle between two extraction direction	8°40′
Beam energy	50–80 keV
Beam current	40–70 A
Pulse length	10–100 s
Beam power	2–4 MW

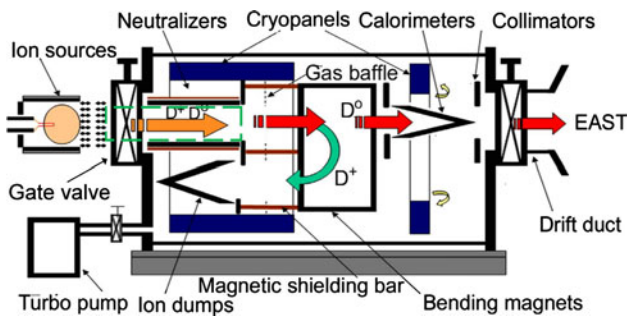

Fig. 1 The sketch of the neutral beam injector for EAST

the problem is how to attain each π_{opt} in the neutralization region of EAST injector. Another problem is that abundant gas will effuse from each end of the neutralization region, imposing the re-ionization losses of neutral beam downstream [6] and the collision losses of ion beam during the acceleration. To compromise the problems, the Direct Simulation Monte Carlo (DSMC) approach has been introduced as a modeling tool to study the gas flow in the neutralizer of neutral beam injector [7]. In the work reported here, the modeling tool based on DSMC [8] was modified and used to simulate the gas flow in the neutralization region of EAST injector, to provide design calculations, and to obtain a better understanding of the formation mechanism of target thickness.

Neutralization Region Description

The positive ion source of EAST injector is a hot-cathode source named bucket ion source, which consists of plasma generator (called arc chamber) and a four grid accelerator [9–11]. The accelerator is adopted multi-slot electrodes system, which can afford larger extraction area and higher current beam than multi-aperture electrodes. The beam cross section is 0.12 × 0.48 m^2, and the beam divergence is 1.2° perpendicular to the slots and 0.6° parallel to the slots. To avoid electric conduction around the atmospheric environment, the insulators of accelerator are designed long enough, forming a space (0.18 × 0.52 × 0.25 m^3) for neutralization.

Gas cell neutralizer has been widely used in the NBI systems and other neutral beam devices, which can provide adequate neutralization efficiency for the positive deuterium beam under 100 keV. The gas cell neutralizer design is determined principally by beam size and energy. The transverse dimension of EAST neutralizer is 0.14 × 0.48 m^2 according to ion beam cross section. As indicated in Ref. [4], the optimum target thickness increases with the beam energy for the positive ions. A long neutralizer can offer optimum target thickness at low gas inlet quantity and maintain a low pressure at the exit, reducing the gas load to the vacuum system and the re-ionization loss of neutral beam. However, the disadvantage of long neutralizer is also pernicious. Because of inevitable beam divergence, it induces more beam losses on the heat loading components along the beamline [12]. The pressure demand at the end of the neutralizer is under 0.03 Pa [13]. Since both desired target thickness and pressure demand are fixed, gas flow calculations show the length neutralizer of 1.12 m can meet the requirements [14].

The gate valve is necessary for the vacuum tank, which will shut down when the injector is in rest period or has some emergencies. Its interior diameter is about 0.65 m and the length is around 0.4 m. For the convenience of installation, the hole on the mounting flange of vacuum tank is larger than the cross section of neutralizer, leading to some slots where the gas could escape.

There are two gas sources in the neutralization region of EAST injector, one is the excessive gas injected from the arc chamber and passing through electrode grids. The other one is a gas feeding hole on the wall of neutralizer. For a real beam, the intensity will have a Gaussian shape centered about the axis of symmetry [15]. Hence, a Gaussian shape to the transverse profile of is desirable in a real neutralizer.

Calculation Model

To compute the gas flow in the absence of beam, a two dimensional (2D) physical model of the neutralization region of EAST injector is built, and its dimension is displayed in Fig. 2. Since the cross section of neutralization region is rectangular mostly, the Cartesian coordinate is adopted in the model. The ditch is used to simulate the large circular part and the slot is supposed to be only 0.02 m. The end of neutralizer is assumed to connect a vacuum condition. The boundary on the grid side is simplified to diffuse reflecting wall, but 77 % of the molecules reflect at the same place and 23 % of them reflect at another place on the same wall [16]. The other two boundaries are also diffuse reflecting walls. Gas from the arc chamber is supposed to inject uniformly on the grid

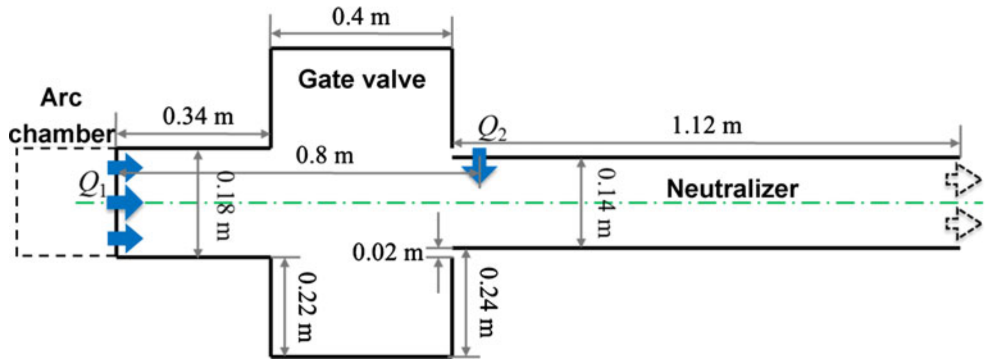

Fig. 2 2D physical model of neutralization region in the EAST neutral beam injector

Table 2 The properties of deuterium gas

Parameter name	Quantity
Molecular mass	6.69×10^{-27} kg
Molecular diameter	2.92×10^{-10} m
Reference temperature	273 K
Viscosity-temperature power law	0.67
Number of degrees of freedom	2

side. Actually, the gas feeding hole of the neutralizer is on the top, but it's on the flank in the model for decreasing 2D simplification error.

The temperatures of the gas and walls are all set equal to 293 K in the absence of beam. The velocities of inject molecules follow the Maxwell–Boltzmann distribution law. Pay attention that the inflow quantity from arc chamber here is a net value in equilibrium state. In addition, as the vacuum degree of gas flow and the smoothness degree of wall are not very high, the velocities of reflected particle from the walls also follow the Maxwell–Boltzmann distribution law [8]. The Variable Hard Sphere (VHS) model was adopted to simulate the molecular collisions. In such model, the scattering between two molecules is isotropic, but the cross-section decreases as the relative velocity increases. The additional properties of deuterium gas adopted in the model are summarized in Table 2.

Results

In the calculation, the deuterium gas is supplied from arc chamber and neutralizer respectively, and the hybrid inlet gas model attracts more attention in the presence of beam. The gas flow rate of either gas source is equal to 15 Torr l/s for demonstration. The computational domain is divided into many identical rectangular grids whose length is 0.02 m and width is 0.01 m, and each grid is divided into 2×2 subgrids.

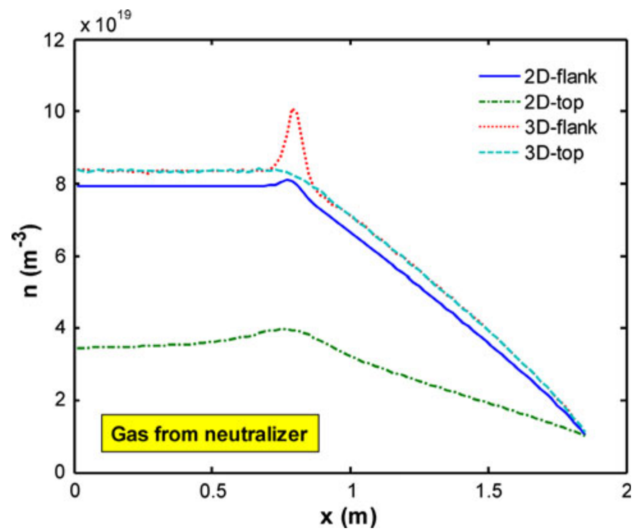

Fig. 3 Centerline density of different 2D/3D simplified model to test the accuracy of current model

Before using the model on the neutralization region, it is first simplified to a rectangular model without the ditch that could be verified by comparison with a 3D model whose transverse dimension was similar to that of neutralizer. The gas was entered into the neutralizer from different side, and Fig. 3 brings out centerline density result. The gas entered into the currently using 2D model is from flank side, which has a good agreement with the 3D results. However, the gas density of 2D model is a little smaller than that of 3D model. Besides, by comparison of two 3D results, it is more possible that there is little intensive density region along the centerline in the actual gas flow.

Flowfield in the Neutralization Region

The calculated velocity fields of the two schemes are shown in Fig. 4. Through the large cross section of accelerator, the deuterium gas effuses gently into the neutralization region like a normal laminar flow. But the

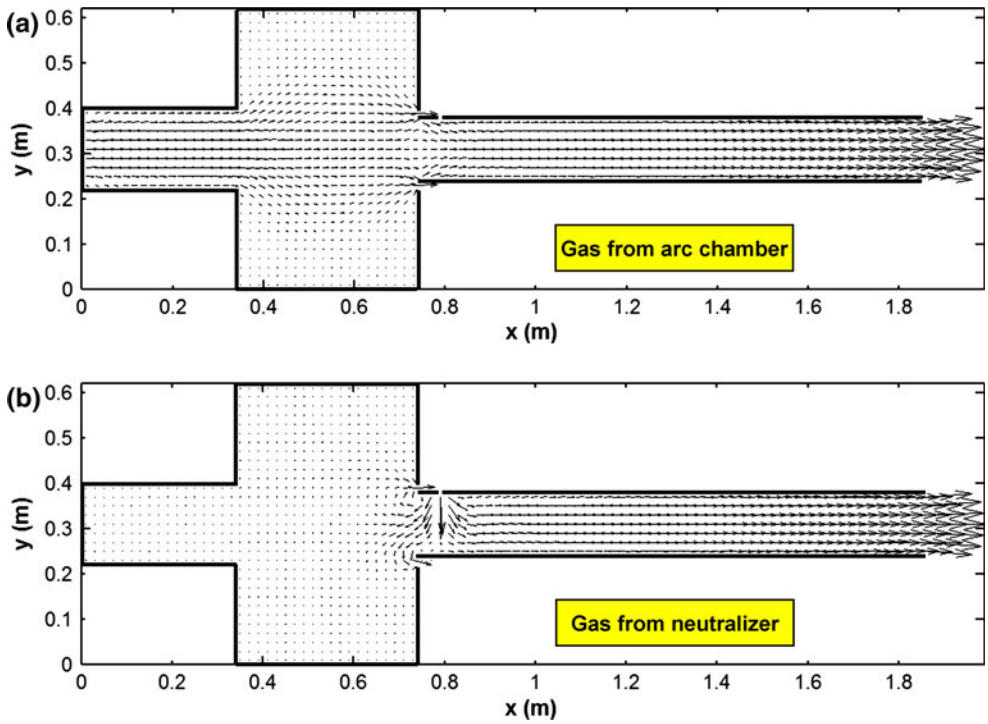

Fig. 4 Velocity fields of gas flow in the neutralization region

gas spreads around immediately when entering the ditch area and the axial velocity stops growing and turns less sharply. Because of the larger transverse dimension in the ditch area, the viscous effect of metal wall to the gas flow becomes weak to the gas flow, leading to an increase of mass flow rate. Meanwhile, the ditch provides a large space for the gas to bring into a near equilibrium, which can be verified in the density contours (shown in Fig. 5). The slot in the ditch connects to vacuum condition, drawing out the gas due to high pressure gradient. And then, the gas moves from the expansion ditch into the constriction pipe, causing congestion at the entrance. It can be seen from Fig. 5 that two symmetrical stagnation points generate on the wall, which is a normal result of subsonic gas flowing over viscous flat wall.

In the other scheme, the deuterium gas expands out of the feeding hole at a high pressure ratio compressed and forms a stagnation point on the opposite wall. Obviously, most of upper region is in equilibrium state that, the quantities of velocity vectors are all equal to zero approximately and the gas density also distributes uniformly. The reason is a perfectly diffusing surface used on the grid side, equalizing the stream in two directions along the centerline. Another flowfield feature is two shear regions between the feeding hole and slot pushing the gas out. Especially a ring vortex is formed near the jet dragging the gas to move to the closer slot. The other flowfield property is similar in two schemes that longitudinal pressure gradient is set up from the midplane, which cause the gas turn toward to the end of the neutralization region.

The quantitative analysis is evident with various centerline profiles in Fig. 6, and the difference between the two gas inlet schemes is clearer. The values of the Knudsen number ($Kn = \lambda/L$), which is the ratio of the mean free path to the characteristic length, range from 0.2 and larger than 2 at the outlets, which means that the region falls within the transitional and molecular flow regimes. It is known that, the temperature is proportional to the molecular collision frequency. So the temperature around entrance is a little higher, but less near the outlet caused by the uniform molecular motion in each gas supplement scheme. Considered the vacuum assumption on the end of neutralizer, the temperature of gas should be a bit higher in actual situation. The centerline pressure profile is given here for the comparison with experimental data in future, and it also demonstrates the pressure (<0.03 Pa) at the outlet can meet the requirement mentioned above. And the centerline axial velocity profiles consist with the analysis for two dimensional flowfield.

Performance of the Neutralization Region

The primary concern of the operator in experiment is how to achieve the wanted target thickness in the current design. The former study indicated that such gas flow in the

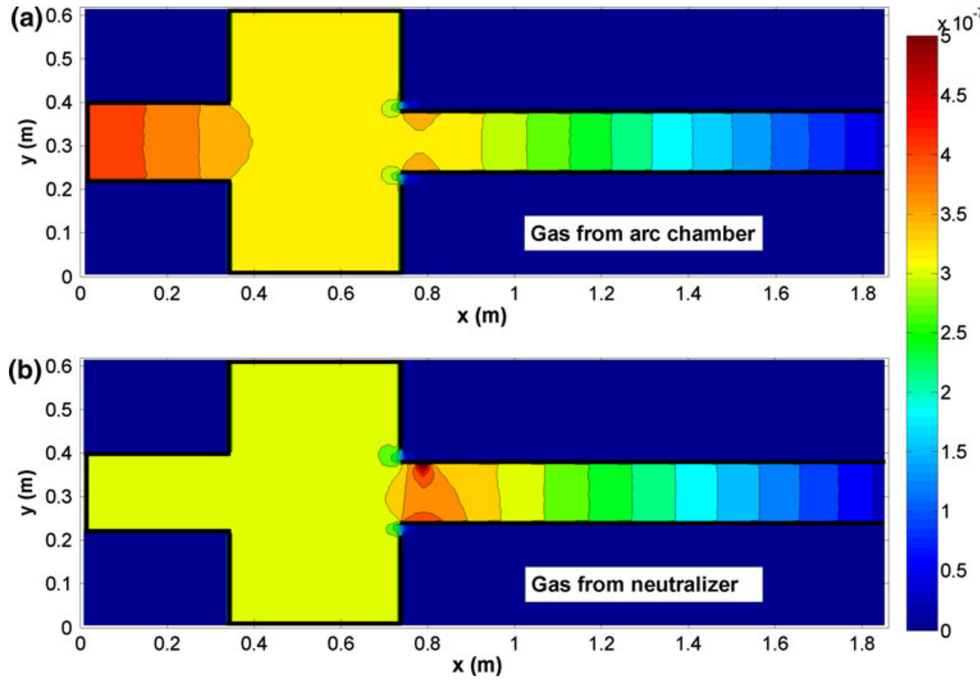

Fig. 5 Density contours of gas flow in the neutralization region (all in kg/m^3)

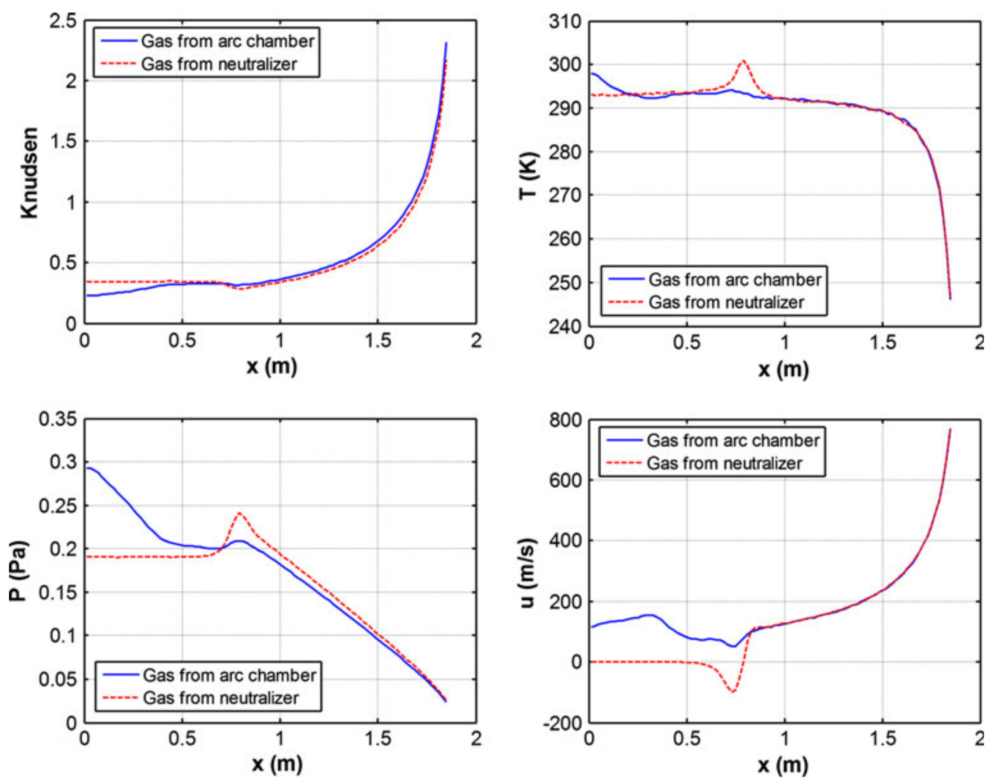

Fig. 6 Various centerline profiles for gas injected from arc chamber or neutralizer

neutralizer was different in the presence of beam that, the target gas will deplete some extent and gas temperature will be higher than 500 K due to the beam-gas interaction [17–20]. However, the result in the absence of beam is still very important to the operation of EAST injector. The target thickness as a function of gas inlet quantity is exhibited in Fig. 7. It is seen that, the curves ascends linearly like molecular flow for moderate gas flow rates but raises more and more slowly as viscous flow for gas flow rates larger than 15 Torr l/s. However, it can be taken that the target thickness is proportionate to the gas flow rates in the operation of EAST injector (under 20 Torr l/s). Besides, the slope of curve for gas injected from arc chamber is 1.2 times as much as that for gas from

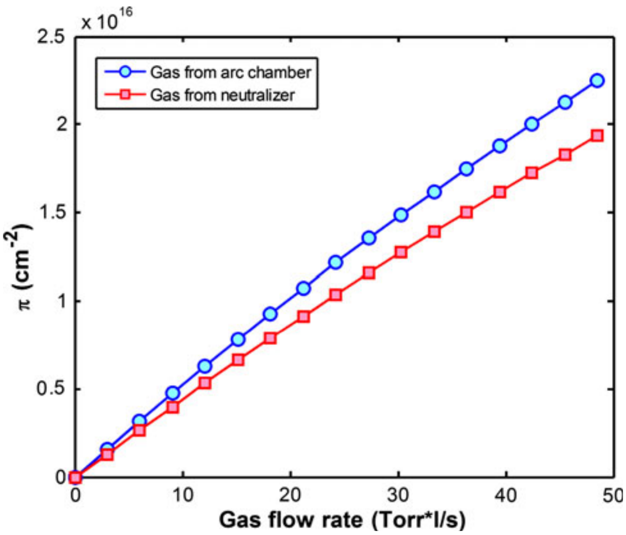

Fig. 7 The gas target thickness plotted against the gas flow rate of arc chamber or neutralizer

neutralizer, which implies that the gas from arc chamber contribute to the formation of target thickness more efficient than that of gas from neutralizer.

Conclusion

The neutralization region of EAST neutral beam injector includes part of the ion source downstream the last electrode grid, the gate valve, the neutralizer and the transitional piping and fitting. A DSMC modeling tool has been adjusted to investigate the gas flow in this neutralization region. The steady-state, viscous and transition region flowfields are generated by injected the deuterium gas from the arc chamber and neutralizer respectively. The quantitative analysis is given through the various centerline profiles, including Knudsen number, temperature, pressure and axial velocity, to demonstrate the flow features. In addition, the target thickness in the neutralization region as a function of gas inlet quantity is calculated in the absence of beam to provide a reference for operation.

Work is in progress to verify these simulation results to measure pressure profiles along the neutralizer in the absence of beam with hydrogen gas injected. Also, a neutralization experiment is about to carry out on the neutral beam test stand, and the neutralization efficiency is measured through the thermocouples installed in a calorimeter plate [21, 22]. Considered the formation mechanism of target thickness is more important in the presence of beam, various high energetic particle collision processes will be embedded to this DSMC code to simulate beam-gas interaction, especially since the beam current is high to 70 A in EAST neutral beam injector.

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