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Simulation of neutral gas flow in the JET sub-divertor

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ABSTRACT

The present work presents a numerical study of the neutral gas dynamics in the JET sub-divertor. A complex model of the sub-divertor geometry is implemented and successful comparisons between corresponding numerical and experimental data have been performed. The experimental data represent the neutral gas pressure obtained by a sub-divertor pressure gauge. The recently developed Divertor Gas Simulator (DIVGAS) which is based on the Direct Simulation Monte Carlo (DSMC) method is applied. DIVGAS is able to predict the behaviour of the flow including macroscopic quantities of practical interest as for instance the pressure, temperature and bulk velocity. The non-linear feedback of the sub-divertor gas flow on the divertor plasma vicinity is not taken into account. For all presented plasma cases, the deduced flow pattern is non-isothermal and covers the free molecular up to the transition flow regime. Furthermore, for low intermediate and high divertor density simulations, recirculation effects occur through gaps between the vertical target tiles, which seem to be two order of magnitude less compared with the recycling ion flux onto the divertor walls.

1. Introduction

Over the last few years much effort has been invested in modeling the neutral gas flow through the complex divertor and sub-divertor region in tokamak fusion reactors [1–4]. The main goal is the investigation of the impact of neutral gas dynamics on the particle removal process and the overall pumping efficiency during plasma operation. Depending on the plasma conditions, the ratio of the mean free path to a characteristic length scale of the divertor, the so-called Knudsen number (Kn), may vary over a wide range. This number in a fusion device covers values starting from the slip regime $\left(10^{-3} \leq Kn < 0.1\right)$ above the dome and close to the divertor targets and the transitional ($0.1 \leq Kn < 10$) or even the free molecular ($Kn \to \infty$, collisionless) regimes in the sub-divertor area and inside the vacuum pumps. Consequently, a reliable estimate of the macroscopic parameters in such a complex system requires a tool to describe the flow in the whole range of gas rarefaction. Currently, to calculate the plasma and neutral conditions in the SOL, the code package which is often used on fluid edge plasma modeling is the EDGE2D-EIRENE code [5], the EDGE2D consists of a 2D plasma fluid code, while the EIRENE algorithm [6] includes a 3D Monte-Carlo solver for neutral–neutral interactions, based on the BGK kinetic model described in [7,8]. Over the years the EIRENE code has been proven to work sufficiently well in neutral modelling. However, no qualitative and quantitative comparison with a more complete neutral code has yet been performed in the sub-divertor region and under various operational plasma conditions. This statement comprises the motivation of this work. It is noted that the classical BGK approximation described in [8], if applied with a velocity independent collision frequency as described in [6,7], it is not able to provide the right ratio for the transport coefficients, namely the ratio of the thermal conductivity over viscosity. Consequently, by using the classical BGK kinetic model, the obtained Prandtl number for a monoatomic gas is equal to unity instead of 2/3 [8,9]. Therefore, the classical BGK kinetic model is commonly applied only for isothermal and pressure driven flows. Most of the earlier EIRENE versions as well as in the ITER-SOLPS code [10] the classical BGK approach is applied. For completeness purposes it is noted that, more advanced BGK models is possible to be considered as for instance the Ellip-

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[1] See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016).

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soidal BGK model (ES-BGK) [11]. The ES-BGK model is a generalized version of the classical BGK, designed to reproduce the physically correct Prandtl number in the Navier-Stokes limit.

In the present study, as an alternative choice for describing non-isothermal flows (as expected in the sub-divertor region), the use of the stochastic Direct Simulation Monte Carlo method (DSMC) [12] is suggested.

The DSMC approach is a particle based method, in which the solution of the Boltzmann kinetic equation is approximated by simulating groups of model particles that statistically mimic the behavior of real molecules. Investigations about neutral gas dynamics in the sub-divertor volume have been performed in the past [13–16], but most of them were focused in low density sub-divertor conditions, where the neutral–neutral collisions do not have a prominent role in the calculation of overall quantities. More recently, a similar investigation on the ITER sub-divertor was performed by successfully implementing the DSMC method coupled with SOLPS input data [17]. It was observed that high recirculation of neutrals behind the divertor targets occur (i.e neutral particles moving backwards to the plasma region). Following this applied workflow, the recently developed Divertor Gas Simulator (DIVGAS), which is a code based on the DSMC algorithm and is capable of modelling neutral gas flows in a tokamak sub-divertor, is applied for all the presented simulations.

The present work mainly focuses on the numerical simulation of the neutral gas flow and the calculation of overall quantities of practical interest i.e. pressure, density, temperature, bulk velocity, recirculation rates etc., inside the complex geometry of the JET sub-divertor by applying the DIVGAS code. For validation purposes, the numerical values are compared with existing JET ITER-Like Wall (ILW) experimental data for the neutral gas pressure distribution in the sub-divertor region presented in [18]. The sub-divertor pressure measurements were obtained with a pressure gauge located at the end of the main vertical lower port of JET Octant 8. The comparison between experiments and numerical data is focused on different L-mode plasma scenarios, which cover a wide range of neutral gas divertor densities. For each case, the corresponding EDGE2D-EIRENE plasma simulations have been performed. Then, the information about the neutral particles on the interfaces along the divertor geometry are extracted and imposed as boundary conditions (BC) for DIVGAS simulations. Following the above steps, a wide range of the Knudsen (Kn) number is being covered (from the free molecular to the transition flow regime) and it made possible to quantify the differences between the numerical and experimental results in each regime.

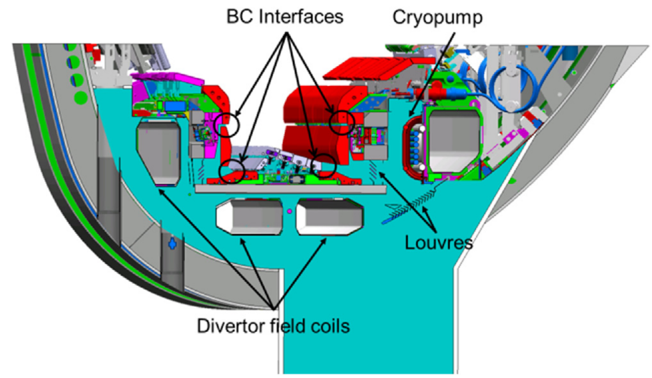

Fig. 1. Geometrical representation of JET sub-divertor structure.

2. Divertor flow configuration

The scope of this work is to examine the 2D behavior of the molecular and atomic deuterium (i.e D_2 and D) binary gas mixture flow inside the JET sub-divertor domain. Fig. 1 illustrates the used 2D-cut of the 3D JET CATIA model of the JET Octant No. 8. The cyan area highlighted in Fig. 1 was chosen as the simulation domain for the DIVGAS calculations. Moreover, in Fig. 1 the four gaps, with which the sub-divertor area communicates with the divertor plasma, are depicted. These four locations are assumed as the interfaces on which the corresponding macroscopic quantities are extracted from EDGE2D-EIRENE calculations and then are used as incoming boundary conditions for the DIVGAS code. In the rest of this work the following names for each gap of Fig. 2a are used, namely upper Low-field side (LFS) gap, lower LFS gap, upper High-field side (HFS) gap and lower HFS gap.

Although the selected geometry is simplified, it still preserves a high degree of complexity of the overall divertor structure, which limits the overall conductance of the system. In addition, the present configuration includes the cryopump and corresponding radiation shielding (louvres), the main lower port duct and the

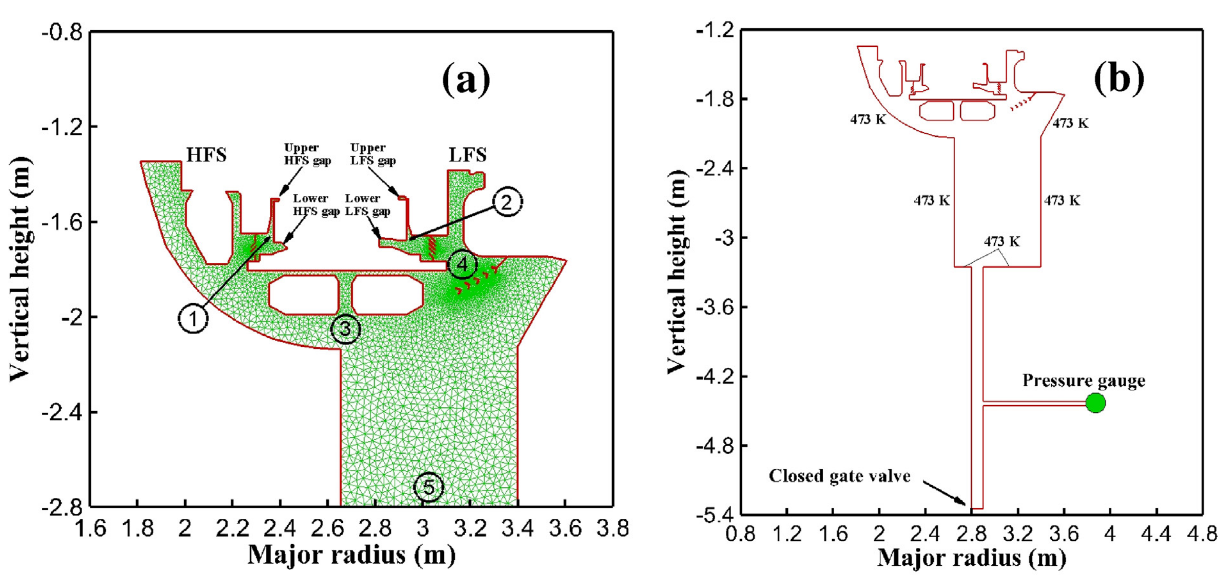

Fig. 2. (a) Various locations (probes) in the sub-divertor area, the applied numerical grid and the boundary interfaces. (b) The exact location of the surfaces with T_{wall} = 473 K are shown. For the rest of the surfaces the wall temperature is 300 K.