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Effect of divertor performance on the pumping efficiency in DEMO

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Abstract. One of the important design drivers of the DEMO divertor development is to ensure a desirable divertor performance at high pumping efficiency by varying, for example, the divertor dome height and pumping port position. In this paper we analyse a generic DEMO divertor design with the pumping port located at the bottom of the divertor. This position has been assumed reflecting earlier work which showed that an asymmetric position of the pumping port relative to the gaps can cause strong reflux of particles. Optimization of the dome height and its effect on neutral compression is made by using the DIVGAS code based on the Direct Simulation Monte Carlo method. The numerical analysis includes the calculation of neutral density in the private flux region and the overall conductance of the sub-divertor structure, which consequently affects the estimation of the effective pumping speed and the achievement of detachment. In the case of pumping port at the bottom of the divertor the neutral flow pattern exhibits more symmetrical distribution than for the asymmetric case and with no outflow to the SOL. It is shown that the divertor configuration with dome impedes the reflux of neutrals towards the plasma through the x-point.

1. Introduction

The design of the DEMO divertor cassette requires a new assessment of the role of the divertor dome structure under reactor conditions. The primary function of the dome is to achieve a high compression of neutrals in the private flux region in order to make the pumping efficiency and helium removal from the reactor more efficient. It also can affect the neutral density upstream of the divertor, and thus influence the achievement of detachment conditions. Additionally, the dome could reduce the neutral reflux to the core plasma through the x-point and shield the pump duct from neutrons. On the other side, it shadows the bottom surface of the divertor cassette from neutrons (which otherwise could theoretically be used for installation of a breeding blanket), increases the complexity of the divertor design and, eventually, the machine cost.

The re-assessment requires the investigation of the neutral flow field in the whole range of gas rarefaction. For this task we utilize a new and efficient numerical tool called DIVGAS, which is based on the Direct Simulation Monte Carlo (DSMC) method [1]. In this method, the solution of the Boltzmann kinetic equation is circumvented by simulating group of model particles that statistically mimic the behaviour of real molecules for an arbitrary level of the gas rarefaction. The calculation of macroscopic parameters of practical interest is based on averaging the microscopic quantities in each grid cell of the flow field. This method has been used to model the neutral gas flow in the JET sub-divertor and a successful comparison with corresponding experimental results has been performed [2]. Additionally, the DIVGAS code has been applied for the simulation of the JT60-SA sub-divertor and successful comparison with the corresponding plasma code SONIC-NEUT2D has been conducted [3].

First results of a comparison between divertor operation with and without the dome have been performed for the ITER divertor with a lateral position of the pumping port and reported in [4,5]. The analysis showed the importance of the dome mainly due to the neutral gas compression, which is beneficial for helium exhaust.

The first assessments of the dome effect in DEMO ITER-like divertor design have been reported in the framework of a free molecular approximation (collisionless case) in [6] and under consideration of collisions in [7]. It was found that the DEMO dome structure can facilitate the pumping efficiency (about 2 times) and protect bulk plasma from reflux of neutral particles from the private flux region (PFR). In the DEMO reactor, the major radius is assumed 1.5 times larger than in ITER [8]; therefore the size of the DEMO ITER-like divertor cassette and the divertor plenum is bigger than that in ITER. Also, the neutral density in the PFR could be high since the average bulk plasma density in DEMO is equal to or higher than that in ITER. This tendency has been observed in Alcator C-MOD experiments reported in [9]. Furthermore, just recently, a sensitivity analysis of a divertor pumping performance for two extreme dome cases (with and without) and different pumping port locations has been performed in [10] and it was found that the pumping port location plays a significant role in the divertor pumping efficiency.

The overall numerical analysis done with the DIVGAS code includes the calculation of pressure, density and temperature fields as well as the gas flow pattern in the sub-divertor area.

2. Conventional divertor DEMO design

In this work we present results of the calculation of the dome effect on the pumping efficiency and the molecular deuterium flow characteristics in the DEMO conventional divertor with only vertical divertor targets, while the pumping port has different sizes in the poloidal direction and is located at the divertor floor. The pumping port is always fixed in the middle of the bottom surface. In Fig.1 the sketch of the suggested DEMO design is considered with the dome at two distances, namely 0.85m and 0.65m from the bottom of the divertor, including the case without the dome. The deuterium molecules are assumed mainly in the PFR and are removed through the pumping port at the bottom of the divertor plenum.

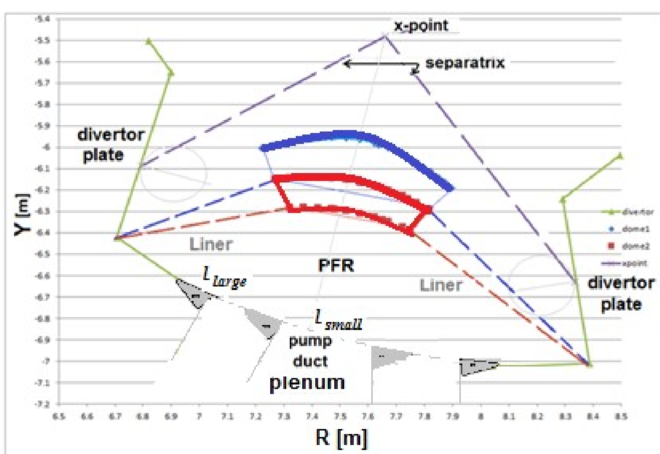

Fig. 1 The 2D model of the DEMO divertor design with different dome heights is presented, including two sizes of the pumping port. The PFR below the dome is separated from the plasma fan by transparent side liners (dashed lines); X(m) coordinate corresponds to the major radial position.

Two poloidal lengths of the pumping port are assumed, namely 0.6m and 1.2m. The total pumping surface area is obtained by taking into account that in the toroidal direction the pumping ports are toroidally discontinuous. The current design includes 18 divertor cassettes with one pumping port in each cassette. The neutrals penetrate the subdivertor region through the low field side (lfs) and the high field side (hfs) gaps (see Fig. 1), where in the case of maximum dome height the length of each gap is 0.94m and 0.66m, while in the case of minimum dome height 0.87m and 0.63m respectively.

3. Numerical approach and boundary conditions

The molecular deuterium gas flow in the sub-divertor area has been simulated using the DSMC algorithm [1]. Since DSMC has been proven to be a reliable method to describe the behaviour of rarefied gases, detailed description of this method has been largely covered in [3,4] and here only the essential aspects of the implementation are mentioned. Briefly the simulated number of particles for all calculations ranges between $2x10^7$ to $3x10^7$, while the time step is equal to Δt=0.5μs. The total number of the computational cells is of the order of $5x10^5$. Each simulation needs about 3-4 days for reaching steady state conditions.

During the simulation, molecular gas deuterium enters the sub-divertor area through the two HFS and LFS liners with given reference pressure P_0 and temperature T_0 similar to ITER case and equal to 10 Pa and 4023 K (or 0.346 eV) respectively (see Fig. 1). When the neutral particles hit a stationary wall then a purely diffuse reflection takes place, where the incident particle is reemitted with Maxwellian distribution based on the wall temperature, equal to T_{wall}=420K. In the case of a particle intersecting with the pumping surface, this particle can be completely removed from the computational domain according to a given probability, which is called capture coefficient ξ. Actually, capture coefficient ξ equals to the ratio of the pumped particle flux over the incoming particle flux. Consequently, ξ takes values between $0 \le \xi \le 1$. It is noted that ξ represents the imposed condition of fixed pumped particle flux and is related with the effective pumping speed of the pumping surface. In the present work the capture coefficient takes the following values, namely $\xi = 0.1, 0.3, 0.6$. If the particle is not finally absorbed from the pumping surface, then the particle undergoes a diffuse reflection, assuming that the temperature at the entrance to the pumping port is equal to 420 K. Finally, when a particle hits the dome structure then in the case of having a dome, the particles are reflected diffusely towards the sub-divertor area, while in the case without a dome the particle is deleted from the domain. The latter assumption can be very well justified, since an interaction with the plasma takes place and results in the immediate ionisation of the neutral particle. It is noted that in the present work the ionization, dissociation or recombination processes are not taken into account. The global particle balance in steady-state operation implies that the net incoming particle flux entering the PFR equals to the pumped particles. This criterion was used for checking the code convergence.

4. Effect of the dome height and pumping port size.

Contour plots of the particle streamlines and the gas pressure are discussed below. In Fig. 2, it is seen that in the case with the dome the incoming gas from LFS and HFS flows towards the pumping port and the existence of the vortices below the dome is observed at low values of ξ (see Fig. 2a and 2b). The size of the vortices increases by decreasing the dome height and they are eliminated for higher values of ξ (see Fig. 2b and 2d). The calculations confirm that in the case of a smooth divertor geometrical configuration, namely without curved surfaces or complex structures etc, the flow pattern appears to be more homogeneous compared with the corresponding results for the ITER-like DEMO divertor design presented in [9], where strong vortices were observed. Additionally, no outflow to the SOL region is found. In general, the pressure which is the main flow driver in the sub-divertor region is higher for low values of ξ (see Fig. 2a and 2c).

In Fig. 3, it is shown that in the case of the small pumping port size, the flow pattern and vortices are similar with the ones in Fig. 2, while quantitatively the sub-divertor pressure for all cases increases.

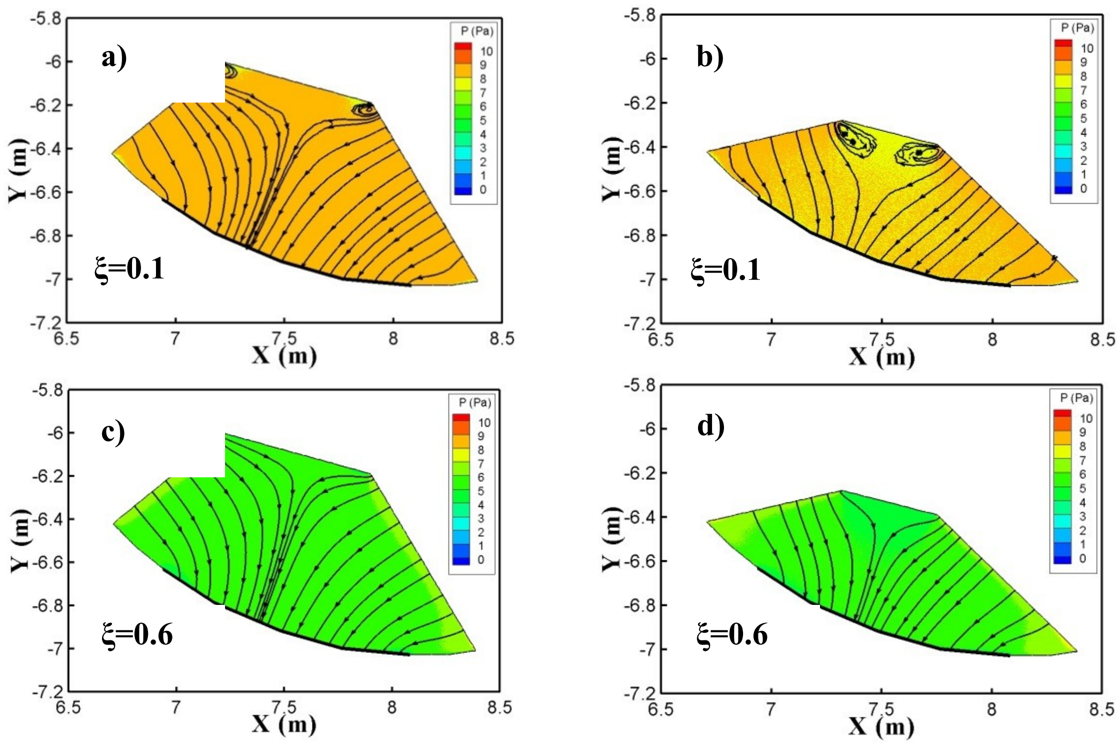

Fig. 2 Pressure contours and streamlines for maximum and minimum dome height and large pumping port size. The sticking coefficient is equal to ξ=0.1 and 0.6.

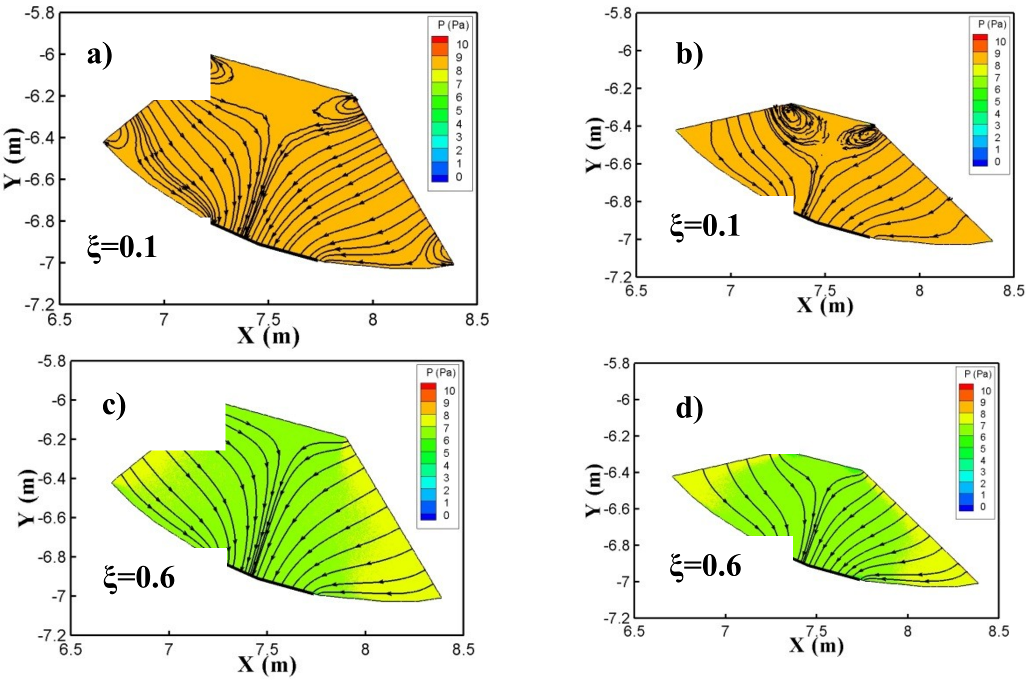

Fig. 3 Pressure contours and streamlines for maximum and minimum dome height and small pumping port size. The sticking coefficient is equal to ξ=0.1 and 0.6.

In Fig. 4 and 5 the number density and temperature distribution along the dome height (see the vertical line in the inserted picture) is depicted for the case of minimum dome height, for ξ = 0.1 and 0.6 and two pumping port sizes. A small variation of both macroscopic quantities is observed. The increase of density and decrease of temperature below the dome is explained by reflecting cold particles from the dome bottom surface. At the pumping port position the increase of density and decrease of the temperature is also explained by reflecting back cold particles from the divertor plenum and this effect is more pronounced for the low ξ cases.

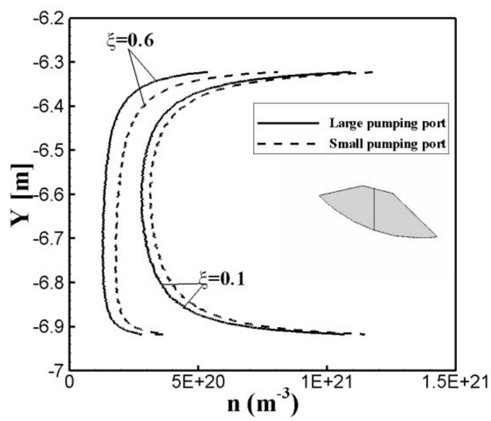

Fig. 4: Number density contour for ξ = 0.1 and 0.6 and two pumping port sizes.

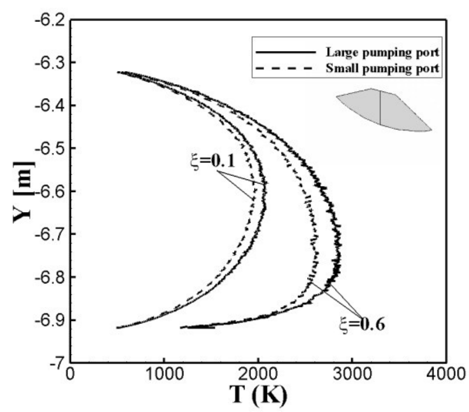

Fig. 5: Temperature contour for ξ = 0.1 and 0.6 and two pumping port sizes.

Additionally, the calculations show that in general the molecular gas pressure is higher in the configuration with the dome and for maximum dome height and small value of sticking coefficient, whereas the pressure is almost independent on the pumping port size.

On the other hand, the gas temperature is higher in configuration without dome and increases with ξ, whereas the highest density is observed in the case with dome and high ξ. For low dome height both the density and temperature are, in general, lower at any value of ξ.

5. Particle balances.

For the given boundary conditions at the entrance to the PFR, the particle flux is proportional to the poloidal length of the HFS and LFS entrance. For the case of maximum dome height the overall (i.e. the sum of the individual fluxes in LFS and HFS) incoming particle flux is equal to $1.8\text{x}10^{25}$ s^{-1} and for the case of minimum dome height is equal to $1.7\text{x}10^{25}$ s^{-1}. These numbers take into account that the total toroidal length is equal to 2πR, where R=8.8 m [8] is the major radius of the device. In Fig. 6 and 7, the pumped flux normalized to the corresponding overall incoming flux for the case of large and small pumping port size and for maximum and minimum dome height is presented. It is seen that the pumping flux is higher for the large pumping port and increases with ξ, whereas there is no large dependence on the dome position. In the case without dome the same tendency is observed. This behaviour is typical for a low Knudsen flow regime. Furthermore, the pumped flux for the case without dome varies between 0.1 and 0.5 by varying with ξ.

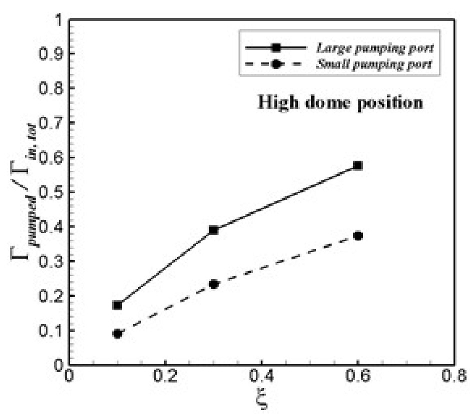

Fig. 6: Pumped flux for different pumping port sizes in configuration with high dome position vs. sticking coefficient ξ.

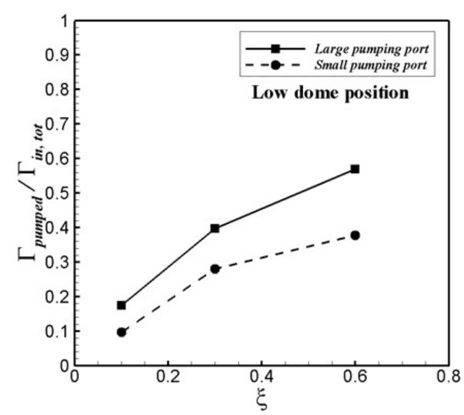

Fig. 7: Pumped flux for different pumping port size in configuration with low dome position vs. sticking coefficient ξ.

In Fig. 8, the outflow from the PFR towards the bulk plasma for the case of large and small pumping port is shown as a function of ξ. The outflow ranges between 30-50% of the overall input flux depending on sticking coefficient. It is shown that in the case without dome the outflux can be reduced with increasing the pumping efficiency; however it cannot be completely eliminated.

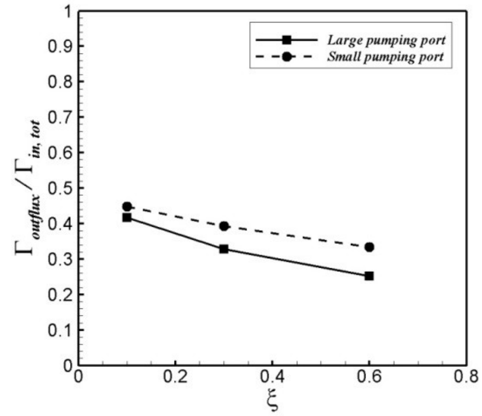

Fig. 8: D_2 outflow vs ξ for the case without dome and for large and small pumping port size. The geometrical configuration corresponds to the maximum dome position.

6. Conclusions

A new DEMO conventional divertor configuration with different height of the dome position and the size of pumping port is investigated in respect to pumping efficiency and D_2 macroscopic quantities in the private flux region and divertor volume.

The DIVGAS code calculations show that it is preferable to have the maximum height of dome position where the particle influx from both the HFS and the LHS to the PFR is higher and additionally it is preferable to have the large pumping port size, which corresponds to the highest pumping flux at any sticking coefficient. These results are valid for small Knudsen number of neutral gas flow in the PFR which is justified by the imposed boundary conditions.

The calculations show that the flow pattern in a smooth divertor geometrical configuration under consideration, namely without curved surfaces or complex structures etc., is more homogeneous (with small vortexes appearing mainly at low sticking coefficients and for the small port size) compared with the one found in the ITER-like DEMO divertor design [9].

Additionally, it is observed that in this configuration the pumped particle flux varies between 30-50% by increasing the pumping port size in the poloidal direction.

The molecular gas pressure is higher in the configuration with the maximum dome height and small value of sticking coefficient, whereas it is independent on the pumping port size.

The gas temperature is higher in configuration without dome and increases with ξ, whereas the highest density is observed in the case with dome and high ξ. For low dome height both the density and temperature are, in general, lower at any value of ξ.

It is confirmed that in the new divertor configuration without the dome, a strong outflow of the molecules from the PFR towards the core through the x-point vicinity is expected, similar to the case with the ITER-like divertor. The outflow becomes stronger for smaller pumping port size and sticking coefficient. The neutrals have lower probability of reaching the pumping duct since many of them return to the plasma in the area previously shielded by the dome. Therefore, the dome structure in the DEMO divertor is favourable in reaching the higher pumping efficiency and protection of the x-point region on gas influx with consequent possible thermal instability onset and disruption occurrence.

Acknowledgment

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