Gas dynamics of the linear plasma generator Magnum-PSI

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Abstract. This paper describes the gas dynamics of Magnum-PSI[1], a large area, high-flux plasma generator to be constructed at the FOM-Institute for Plasma Physics Rijnhuizen. The aim of Magnum-PSI is to provide a controlled, highly accessible linear laboratory experiment in which the interaction of a magnetized plasma beam with different surfaces can be studied in detail. The beam parameters will enable a study of plasma surface interaction (PSI) in the range of particle fluxes ($\approx 10^{24}$m^{-2}s^{-1}) and energy fluxes ($\approx$10 MW m^{-2}) expected in the divertor of ITER.

In order to reach the ITER-relevant parameter regime of plasma surface interaction, the neutral pressure near the target must be determined by neutralization of the plasma and additional gas puffing in the target chamber. In order to produce the large plasma flux, however, a cascaded arc will be used, operating at around 10^4 Pa, injecting 40 slm of Hydrogen gas. Using the Direct Simulation Monte Carlo method it was found that a three stage differentially pumped vacuum system can reduce the contribution from the source neutrals to less than 1 Pa.

We will discuss the results of the DSMC gas flow simulations. The influence of the position of the skimmers on the pressure ratio between the different chambers is investigated. The first skimmer faces the supersonically expanding gas from the source and its capability to separate the confined magnetized plasma and the free expanding gas strongly depends on its position relative to the shock that is generated.

Validating simulations for Pilot-psi, a smaller scale forerunner of Magnum-PSI and for Plexis, a similar device at the Eindhoven University of Technology, show good agreement with experimentally observed pressure differences in a two-stage differentially pumped system. For high flows the results agree with the Navier Stokes solution.

Keywords: DSMC, ITER, plasma generator, expansion, shock formation
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INTRODUCTION

The interaction of the magnetically confined plasma with the material wall has been identified as one of the most urgent research topics for the international fusion reactor ITER [1]. Tritium retention and erosion rates presently foreseen are critical issues for prolonged operation. ITER relies on a so-called divertor to remove helium and other impurities from the fusion plasma. The particle and energy fluxes toward the neutralizing target plates of this divertor are tremendous: typically 10^{24} ions m^{-2}s^{-1} and 10 MW m^{-2} continuously[1]. The temperature of the plasma in the divertor chamber is reduced to the 0.5-7 eV range via the radiative cooling that follows the puffing of gases like neon.

Plasma-surface interaction under these conditions is an unexplored area. Even the fluxes in present-day large Tokamaks are too low to enter the regime relevant for ITER and beyond. Present-day linear machines are unable to produce the required high flux at low temperatures over a sufficiently large area to capture material released from the surface in the active plasma. We are presently designing a linear machine, Magnum-PSI [2], that will use an expanding cascaded arc plasma in hydrogen as primary source to yield fluxes relevant for ITER. Magnum-PSI will operate in a steady state high magnetic field (3T) and cover an area of 80 cm^2.

The cascaded arc source [3] is very efficient because it operates at a high pressure. It reaches a degree of ionization between 5 and 10%, depending on the gas that is used. The partially ionized gas leaves the arc with the sonic speed and expands into a vessel at a low pressure, forming a shock structure. One of the requirements to be fulfilled for ITER relevant plasma surface interaction studies is that the neutral pressure in front of the target is determined by recycling, or by gas puffed in nearby, mimicking the situation in the ITER divertor. Thus, the gas leaving the arc must be pumped

[1] Magnetized Plasma Generator and Numerical Modelling for Plasma Surface Interaction

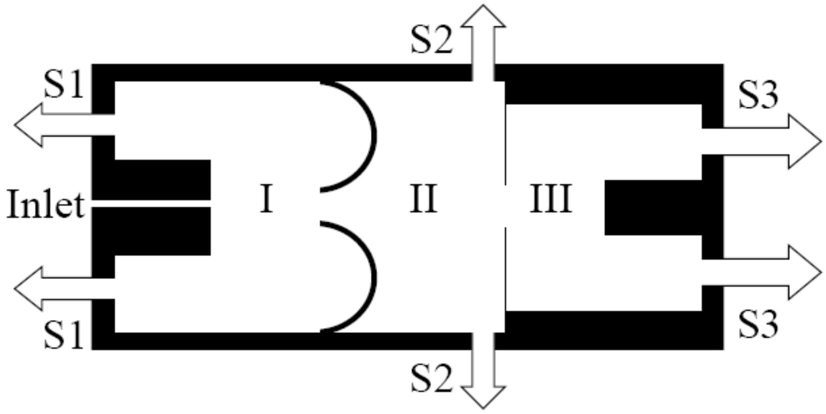

FIGURE 1. Geometry of Magnum-PSI as used in the DSMC calculations, showing the three sections. I is the source chamber, II the heating chamber, and III the target chamber. The axial pumps are S1= 38000 m^3/h and S3=30000 m^3/h. The radial pump S2=33000 m^3/h. Gas flows in through an inlet with a diameter of 2 cm. The distance from the source to the target is 100 cm and the radius is 30 cm

away before it can reach the target, while the plasma beam must flow unhampered.

To achieve this, first a strong axial magnetic field is applied that reduces the expansion of the plasma part, thus separating plasma and neutrals. The coupling with the neutrals is very weak in the supersonic expansion. In addition, the vacuum system is split in three chambers, separated by skimmers. The plasma passes along the axis through the skimmers, while the expanding gas is scraped off and pumped away.

Because the gas expands to low densities and because the pressure in the second and third chamber is also very low, we have decided to model the gas flow using the Direct Simulation Monte Carlo (DSMC) code developed by Bird[4] (DS2V, version 3.4.01). The expansion from the source interacts with the first skimmer in a regime with a high local Knudsen number, determined by the shock and by the radius of the skimmer. Here the position of the skimmer relative to the normal shock of the expansion is an important factor for the gas flow through the skimmer. In this paper we will concentrate on the efficiency of this first skimmer. For validation of the results we also performed simulations for Pilot-psi[2], a smaller scale forerunner of Magnum-PSI and for Plexis[5], a similar device at the Eindhoven University of Technology, used for deposition of thin layers and surface chemistry. Both devices were equipped with one skimmer, resulting in a two-stage differentially pumped system. For high flows the DSMC results are compared with those of a Navier Stokes solver.

GEOMETRY

Figure 1 shows the geometry of Magnum-PSI as used in the DSMC calculations. The gas enters from the left through a narrow channel and flows through the three chambers, each of which is separately pumped. The source chamber (I) contains the supersonic expansion. The heating chamber (II) is used to apply various heating methods, in order to reach the required ITER relevant heat flux. Finally, in the target chamber (III) the plasma beam is neutralized. The interaction of the gas with the plasma is neglected. The neutralization of the plasma on the target plate can be accounted for by a source emerging from the target, equal to the incoming plasma flow. This source is directly related to the obtained degree of ionization in the source and is thus typically 10% of the inlet of gas via the source. The geometry of the experiments used for validation consists of only two sections, leaving out the heating chamber and one skimmer.

THE MODEL

Since the plasma is created inside the arc, the Hydrogen gas is heated. The temperature at the arc exit is taken as 1800 K, and the flow velocity is 4000 ms^{-1}, in agreement with measurements presented in [5]. These data represent the flow characteristics at the end of the nozzle, when the plasma/gas mixture has already expanded. Atoms or molecules are sampled from a distribution with this temperature and flow velocity. The density of the flow is set by the required

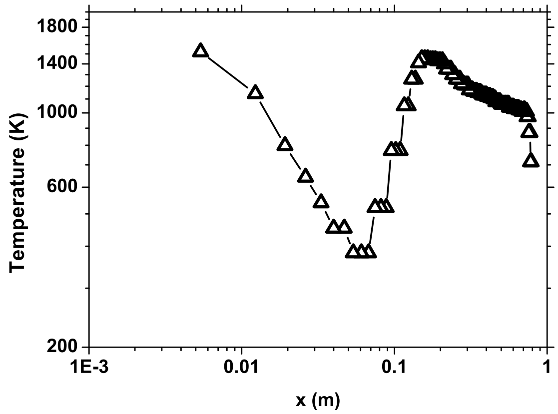

FIGURE 2. Temperature profile along the axis of an expansion in a vessel with a radius of 30 cm and 80 cm long. The background pressure is ≈7 Pa. The inflow is 40 slm H_2 at 1800 K and 4000 m/s through an orifice of 1 cm radius. The shock, expected at 13 cm, is smeared out due to the finite mean free path.

influx, the cross section of the arc outlet (radius 1 cm) and the flow velocity. At 40 slm this yields $1.43 \cdot 10^{22}$ m^{-3}. The simulation is 2-D, assuming cylindrical symmetry. This implies that pumping is smeared out over ring-shaped areas in the axial or radial direction. The capacity of the pumps is modelled by a combination of a pump area and an adsorption probability of 10%. The other surfaces are assumed to be cooled and kept at 300 K. The reflection is diffuse.

RESULTS

The expansion from the source becomes supersonic and a shock structure is formed. Figure 2 shows an example where a flux of 40 slm hydrogen enters a vessel with a background pressure of ≈7 Pa. Modelled is the expansion in a vessel with a radius of 30 cm and a length of 80 cm. This resembles the Magnum-PSI source chamber without a skimmer. Pumping is at the end opposite to the source (≈10 m^3s^{-1}). Shown in figure 2 is the variation of the temperature along the axis of the device. The behavior agrees with the experimental data in [5]. The position of the normal shock agrees with the expression given in [6, 7, 8],

$$x_{shock} = 0.67d\sqrt{p_0/p_b} = 1.8 \cdot 10^{-2}\sqrt{\frac{\hat{\Phi}}{p_b}}\sqrt[4]{A\hat{T}_s}, \tag{1}$$

with p_0 the stagnation pressure, p_b the background pressure, d the diameter of the inlet opening, $\hat{\Phi}$ the influx in standard cm^3 per second, A the mass in atomic units, and $\hat{T}_s$ the inlet temperature in eV. For our settings this yields $x_{shock} \approx 13$ cm. In the simulation the shock is smeared out roughly between 7 and 15 cm because of the locally large mean free path, one of the reasons to use the DSMC method.

For validation against experiments, we simulated the flow in the Pilot-psi device. To study the effect of a skimmer, a second section was created by means of a coaxial chamber with a radius of 13 cm. Both sections were pumped at the side opposite to the source. The skimmer opening was at 8 cm from the outlet of the source.

Figure 3 shows the measured pressure in the two sections for this two-stage differentially pumped device as a function of the gas flow. Of course the effect of the skimmer depends on its diameter. Here the opening has a diameter of 3 cm, yielding a factor 4.5 reduction in pressure. A 5 cm skimmer gave only a factor two reduction. Three cm is still wide enough to let the plasma beam pass unhampered. DSMC results at 3 slm are also plotted. They agree very well.

In Pilot-psi the position of both the source and the skimmer was fixed. In Plexis the source can be moved relative to the skimmer, enabling a study of the influence of the skimmer position. Another aspect of Plexis is the fact that the pump opening is close to the source, similar to the situation indicated for the first section in figure 1. Figure 4 shows the pressure in both sections as a function of the distance between the skimmer and the source. When the skimmer

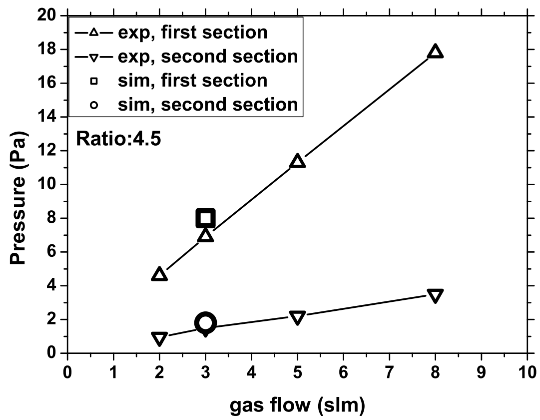

FIGURE 3. Measured and computed pressure in both sections of Pilot-psi. The chambers are coaxial and are pumped at the side opposite to the source. A skimmer with a diameter of 3 cm is applied

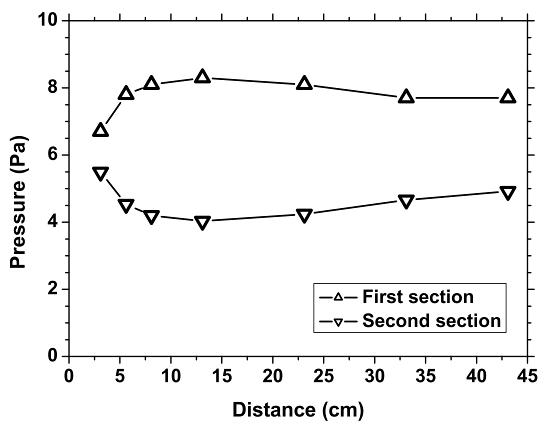

FIGURE 4. Measured pressure in both sections of Plexis as a function of the distance between the source and a 3 cm diameter skimmer. The gas flow is 3 slm of Hydrogen.

is too close, the flow expands directly in the second section, and the pressure is hardly reduced. At large distances, with the skimmer in the subsonic flow behind the shock, the reduction is also small, and becomes independent of the skimmer position. There is an optimum distance, leading to a reduction of the pressure with a factor two.

Figure 5 shows result of simulations in a two chamber system, for different positions of the skimmer. Plotted is the radial profile of the axial flow, $N(r)v_{ax}(r)$, through the skimmer opening for a skimmer of 5 cm radius, positioned at 10, 20, and 30 cm away from the source exit. In the 10 cm case the skimmer is before the shock, 20 cm is close to the shock position, and 30 cm is behind the shock. The gas flow was 75 slm, emerging from a 1 cm radius source. According to equation (1) the shock for a free expansion is expected at 18 cm from the source. The results show that the inflow in the second chamber is significantly reduced when the skimmer is moved from 10 to 20 cm, while a further increase of the distance does not change much, in agreement with the observations in Plexis (Fig. 4). The same behavior is found for the pressure near the radial vessel wall. At 10 cm distance the pressure in the first section is 5.8 Pa versus 4.4 Pa in the second section. This changes to 6.9 vs 3.6 Pa at 20 cm and 6.8 vs. 3.7 Pa at 30 cm distance. Obviously, the position of the skimmer relative to the shock determines the efficiency of the differential pumping. This

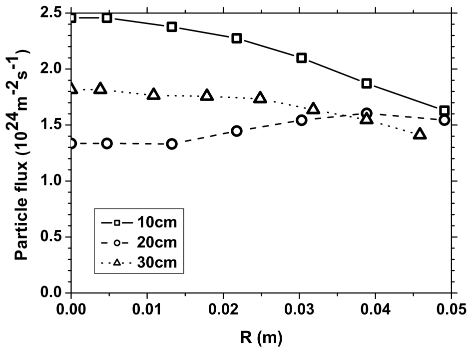

FIGURE 5. Radial profile of the axial particle flux, N(r)v_{ax}(r), through a skimmer positioned at 10, 20, and 30 cm from the source in a two chamber differentially pumped system. The skimmer opening has a radius of 5 cm. The vessel radius is 30 cm and the source is at 60 cm from the pump at the opposite side. The inlet is 75 slm H_2. The results show there is an optimum distance where the inflow in the second chamber is minimized.

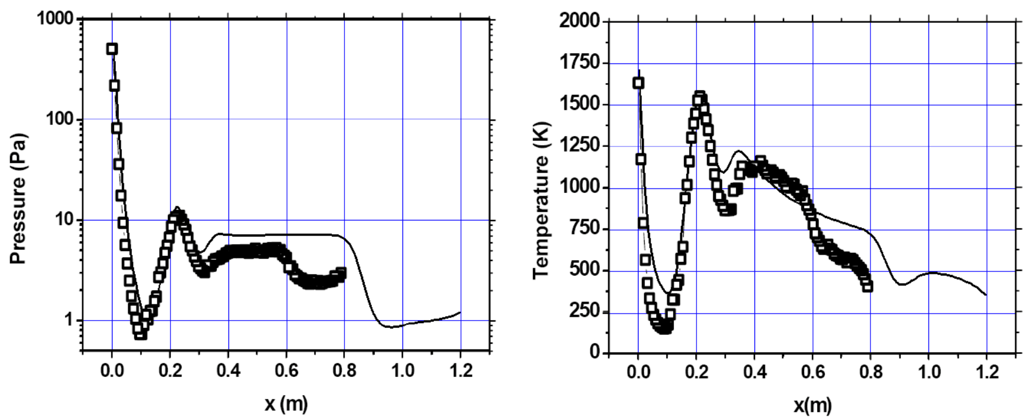

FIGURE 6. Pressure and temperature distribution along the axis of a three stage differentially pumped system, as computed with DSMC (marks) and with a Navier Stokes solver (solid line). The inlet is 75 slm H_2. The first two sections in both simulations are equal; the first skimmer is positioned at 20 cm from the source. In the NS simulation the second skimmer is placed at 83 cm and the target is at 120 cm from the source, compared with 60 and 80 cm in the DSMC calculations. Also the pump speed differs. In the NS simulation the pump speed in the second chamber is 20000 m^3/h and in the target chamber 150000 m^3/h, against the 38000 and 30000 m^3/h for the DSMC case.

is an important issue, because Magnum-PSI will be operated not only in hydrogen, but also in deuterium, helium, and mixtures of these gases, at various flows. Fortunately, a good guess of the distance of the shock can be obtained from equation (1).

Figure 6 shows a comparison between the results of the DSMC simulations and the solution obtained with a Navier Stokes (NS) solver [9]. The skimmer is placed at 20 cm, the optimal position. Again, the flow is 75 slm. The agreement is good in the first section and in the beginning of the second section, behind the skimmer. Beyond this distance the settings in the simulations differ too much to make a useful comparison. The local Knudsen number, based on the gradient in the mass density, is between 0.1 and 0.3 in the region considered for comparison. This explains the differences between the NS and DSMC solutions.

The pressure in the ITER divertor is limited to less than about 10 Pa, because otherwise it becomes opaque for the ions from the main plasma, and looses its functionality. Figure 7 shows that even with the high gas flow applied the pressure in the target chamber resulting from the source neutrals stays far below this limit, offering a large window for experiments with additional gas puffing and recycling near the target. Figure 7 also shows some streamlines. The vortices show a relatively weak coupling between the region near the wall and the center, where the plasma beam

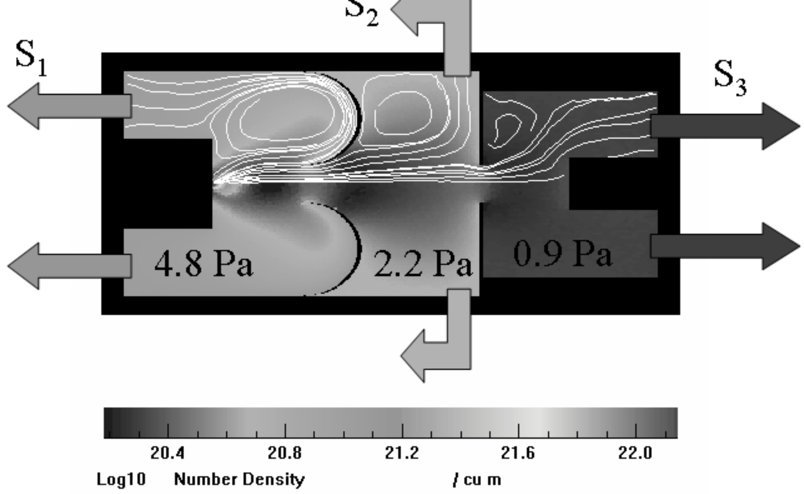

FIGURE 7. Density distribution in the gas flow of Magnum-PSI as computed with DSMC. The inlet is 40 slm H_2.

passes through. Due to the large mean free path vibrationally excited molecules originating from association of atoms at the wall can penetrate the plasma, leading to molecular enhanced recombination. For hydrogen plasmas this is one of the main destruction channels.

CONCLUSIONS AND OUTLOOK

The gas load at the target of Magnum-PSI, originating from the use of a high pressure cascaded arc plasma source can be reduced to the level needed for ITER relevant plasma surface interaction experiments by using a three stage differentially pumped vacuum system. The optimal position of the first skimmer relative to the source depends on the position of the normal shock in the expanding gas flow from the source. The skimmer should be placed just beyond this shock. DSMC calculations reveal that the shock is smeared out over a number of mean free pathes, but that estimates based on entropy considerations (1) still hold. The DSMC simulations, validated against experiments and Navier Stokes solutions, provide a good tool to analyze the design of the vacuum system of Magnum-PSI at the low pressures expected.

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