Preliminary assessment of deterministic kinetic modeling for neutral particles in the JET sub-divertor

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INTRODUCTION

Proper modeling of the neutral gas flow in the divertor and sub-divertor areas in tokamak fusion reactors, is of major importance to the exhaust pumping process and the overall pumping efficiency, and therefore directly influence the design of the machine. Despite the implementation of EIRENE [1] being a very reliable and effective approach, drawbacks deriving from the stochastic nature of the algorithm, such as statistical noise and computational cost, which are significantly increased in high collisional regimes, led to the implementation of more advanced kinetic stochastic codes (DSMC) [2,3] or of deterministic neutral fluid models [3,4] with considerable success.

In the present work, instead of adopting a stochastic approach, an in-house computationally efficient kinetic deterministic solver, utilizing a novel marching discrete velocity method (DVM) on unstructured grids [5] is developed and implemented to model the neutral particles in tokamak exhaust systems. The Boltzmann equation is accordingly replaced by suitable kinetic model equations, which are numerically solved, in a deterministic manner, by discretizing the particle velocity space via the discrete velocity method and the physical space via finite difference or volume schemes. In the present case, the Shakhov model is implemented and a systematic comparison with corresponding results in [2,3], where the DSMC method is introduced, is conducted to demonstrate the effectiveness and reliability of the present approach.

FLOW CONFIGURATION

The neutral gas flows inside the pumping area of the JET and DEMO nuclear fusion reactors are considered.

In Fig. 1 (up), a simplified geometry derived from a 2D cut of the 3D model for the JET Octant No.8 is plotted. Though simplified, the geometrical characteristics of the divertor coils, the radiation shielding and the cryopump are taken into consideration [2]:

- ☐ Water-cooled louvres and divertor coils are kept at room temperature of 300 K.
- ☐ Outer wall of the vacuum vessel is held at 473 K.
- ☐ Cryopump surface is kept at 80 K.

In Fig. 1 (down), the employed 2D cut of the 3D DEMO model is shown [3]:

- ☐ Outer wall of vacuum vessel is equal to 570 K.
- ☐ The pumping opening is kept at the same temperature with outer walls.

In both flow setups, the gas molecules enter the computational domain via the two openings, namely, high field side (HFS) on the left and low field side (LFS) on the right gaps in Fig. 1 and can move freely in the divertor area.

The interaction of the particles with the pumping opening surface is performed by introducing a capture coefficient ξ_{pump} (number of particles absorbed versus the number of particles hitting the pumping surface).

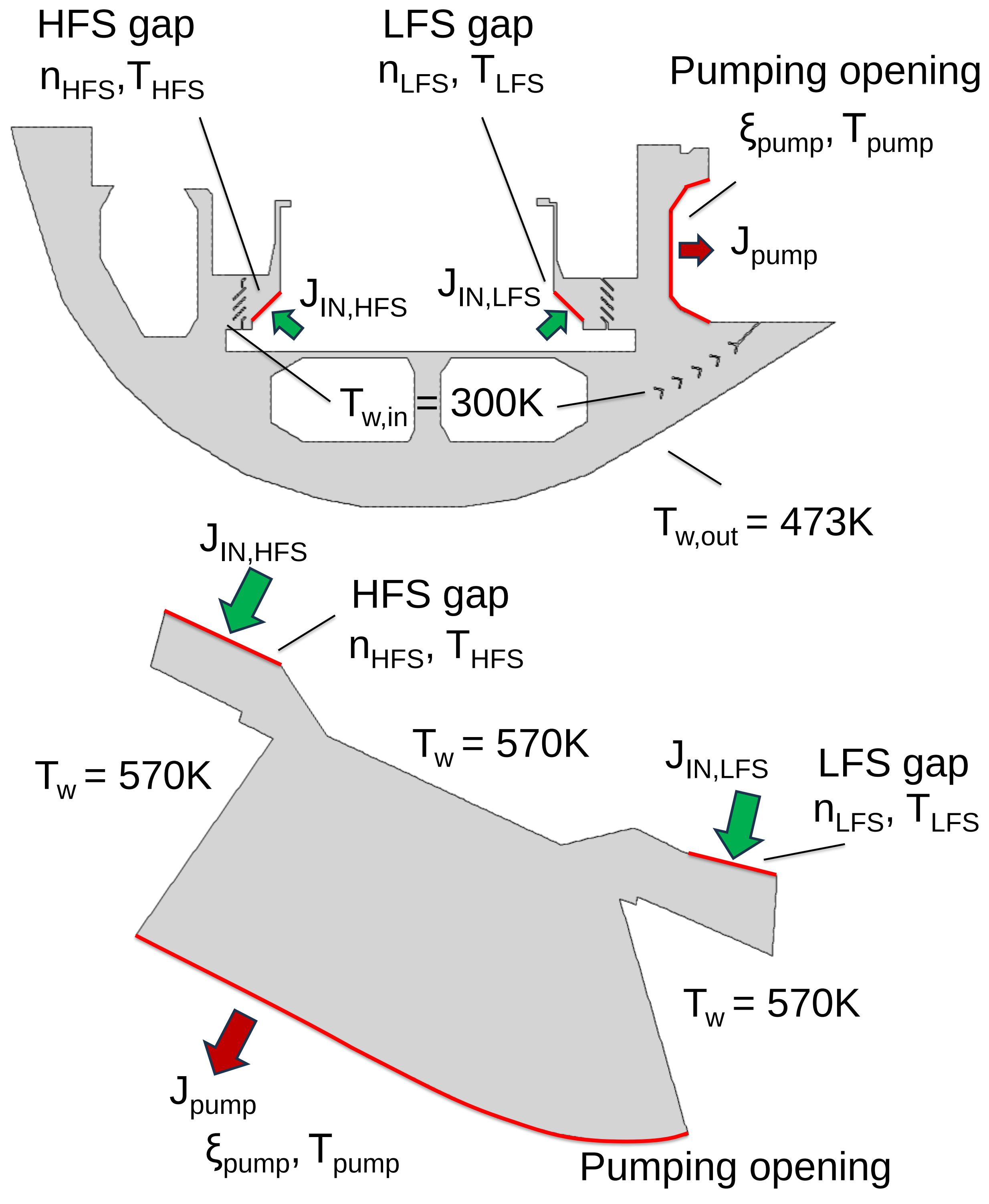

Fig. 1: Configuration and computational domains for the JET [2] (up) and DEMO [3] (down) sub-divertors.

DETERMINISTIC KINETIC MODELING

Any steady-state 2D kinetic model equation (e.g. BGK, Shakhov, ES), in the absence of external forces, may be written in a general form as $\boldsymbol{\xi}\cdot\frac{\partial f^{(t+1/2)}}{\partial \boldsymbol{s}} = \nu\left(f^{eq,(t)} - f^{(t+1/2)}\right)$, where the operator $\boldsymbol{\xi}\cdot\frac{\partial}{\partial \boldsymbol{s}} = \xi_x\frac{\partial}{\partial x} + \xi_y\frac{\partial}{\partial y}$, while $s = s(x,y,\theta)$ denotes the characteristic with polar angle θ, passing from some point (x,y), f is the velocity distribution function, f^{eq} is the local equilibrium distribution function provided by the kinetic model and ν is the collision frequency.

- In the molecular velocity space, a novel DVM is applied.
- In the physical space, an unstructured mesh with $j = 1,\dots,N_E$ elements and $i = 1,\dots,N_N$ nodes with coordinates (x_i, y_i) is implemented.
- Macroscopic quantities are obtained as moments of the distribution function.
- The methodology is implemented in 2D in the physical space but can be readily extended in 3D [5].

RESULTS and DISCUSSION

In Table 1, the ratio of the computed outflux versus the nominal influx, i.e. the albedo coefficients, in both the HFS and LFS gaps of the JET divertor region are evaluated. Four different flow scenarios of deuterium are taken into consideration. It is clearly seen that the comparison in all cases between the DSMC and the Shakhov model is very good, with deviations of about 2% and 1% for the HFS and LFS gaps respectively.

As seen in Table 2, where the normalized pumped particle flux vs various values of the capture coefficient ξ_{pump} is plotted, very good agreement between the DSMC method and the present work is observed. It is seen that as ξ_{pump} is increased, the deviation between the two methods is also increased, never exceeding 9%. This monotonically increasing behavior is believed to depict deviations in the geometrical characteristics between the two pumping surfaces of the two simulation models.

In Fig. 2, indicative contour plots are shown for number density (tup left), temperature (up right), pressure (down left) and streamlines (down right) for deuterium flow through the JET divertor. In Fig. 3, indicative streamlines and velocity magnitude contours obtained by the Shakhov model for helium flow through the DEMO divertor, where all openings (HFS, LFS, pumping) are held in 570 K. Two values of ξ_{pump}= 0.02 (left) and 0.3 (right) are shown. In all cases, very good agreement with [2,3] is observed.

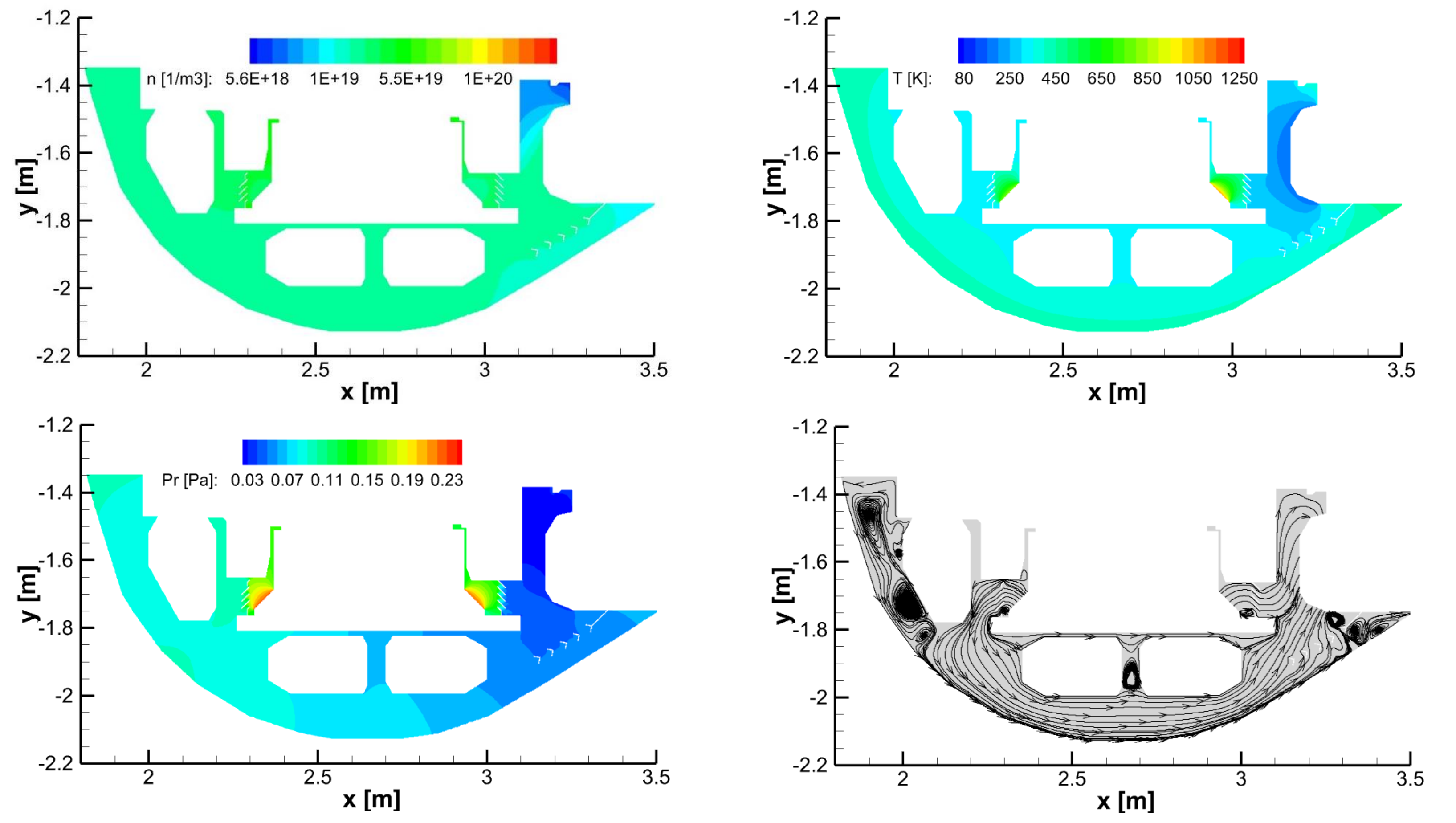

Fig. 2: JET - Number density (up left), temperature (up right), pressure (down left) and streamlines (down right) for deuterium flow and T_{HFS} =1620K, T_{LFS} =2521K, T_{pump}= 80K and ξ_{pump}= 0.15.

Table 1: JET - Albedo coefficient comparison for various flow configurations of deuterium obtained by DSMC [2] and Shakhov model (present work).

	HFS gap			LFS gap		
Case Nr.	DSMC [2]	Present work	Dev. [%]	DSMC [2]	Present work	Dev. [%]
1	0.9	0.918	1.98	0.86	0.864	0.43
2	0.88	0.896	1.77	0.84	0.832	0.9
3	0.92	0.928	0.85	0.85	0.858	0.96
4	0.89	0.909	2.14	0.86	0.862	0.2
Avg.	0.90	0.91	1.69	0.85	0.85	0.18

Table 2: JET - Normalized pumped particle flux comparison for various values of the capture coefficient ξ_{pump} = [0.15, 0.3, 0.6, 1] of deuterium.

	J_{pumped}/J_{in}		
ξ_{pump}	DSMC [2]	Present work	Dev. [%]
0.15	0.113	0.110	2.89
0.3	0.133	0.128	3.54
0.6	0.152	0.142	6.49
1	0.163	0.149	8.36

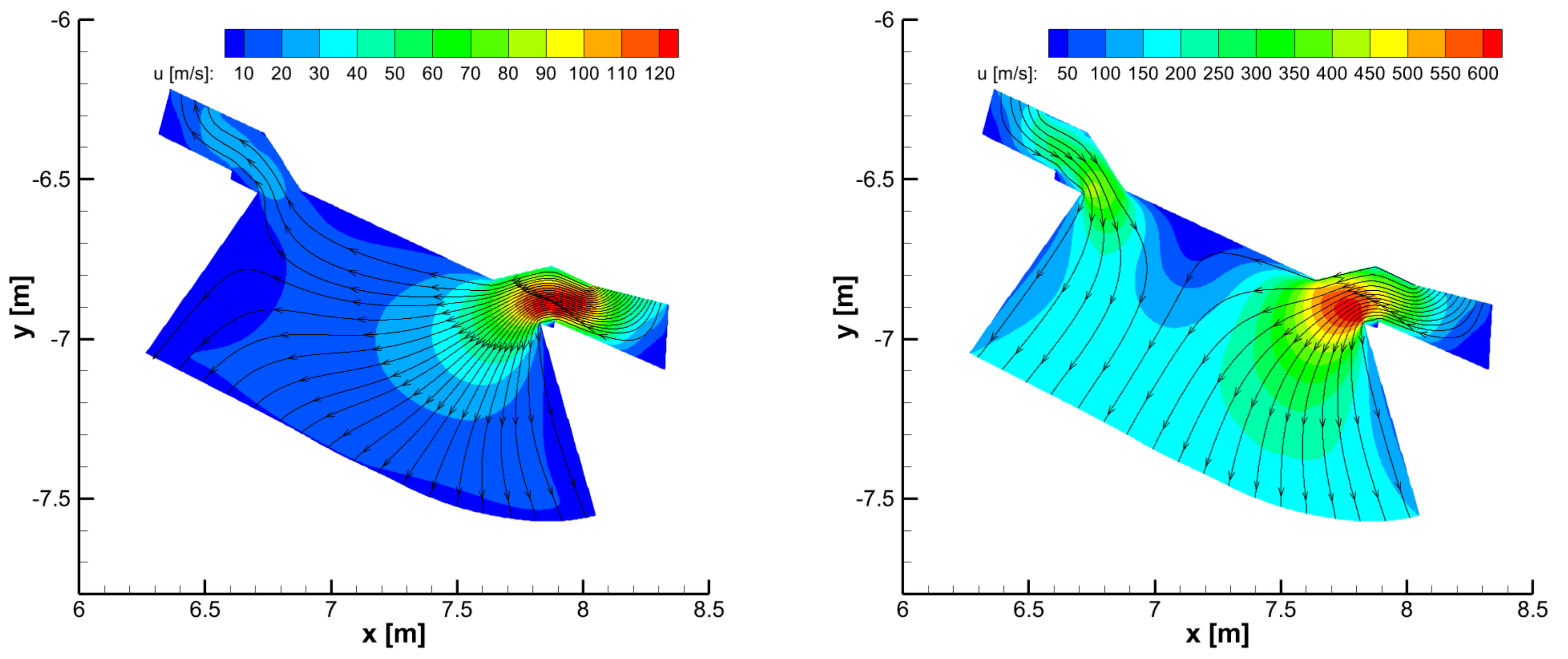

Fig. 3: DEMO - Streamlines and velocity magnitude contours obtained by the Shakhov model for helium flow and T_{HFS} = T_{LFS} = T_{pump}= 570K and ξ_{pump}= 0.02 (left) and 0.3 (right).

CONCLUDING REMARKS

- ❖ The neutral flow of helium and deuterium particles through the divertor regions of JET and DEMO fusion reactors has been successfully investigated by implementing a computationally efficient marching discrete velocity algorithm on unstructured grids.
- ❖ There is very good agreement between the present deterministic methodology and the DSMC method [2,3], for various macroscopic quantities and flow scenarios.
- ❖ The methodology can be applied in various kinetic model equations and it can be extended in a straightforward manner to three dimensions.

REFERENCES

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