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C Day et al.

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Assessment of the operational window for JT-60SA divertor pumping under consideration of the effects from neutral-neutral collisions

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Abstract. The JT-60SA device will start operation in 2019. One of the top research goals is to study high density plasma physics in view of a demonstration fusion power plant. In this context, this paper exemplifies an integrated modelling exercise of the divertor pumping system of JT-60SA, for one of the reference plasma scenarios outlined in the JT-60SA Research Plan (scenario #2 with moderate plasma density but strong gas puffing). Even today, to simulate such a system under consideration of all geometry details and through all collisionality regimes, is beyond the computational state-of-the-art. This paper therefore presents a stepwise procedure, based on two different codes. The logical first step is a zeroth order sensitivity study based on the ITERVAC code to identify the most relevant flow paths of the problem aiming for some sort of simplification and to identify the simplified domain for the detailed analysis. The next step is then to do a more accurate treatment of the sub-divertor neutral gas flow using a collisional approach with the DIVGAS code. It is revealed that the macroscopic properties in the sub-divertor deviate by more than factor two from the collision-free values, which were used for the initial design of the pumping system, but the performance for scenario # 2 is still well balanced and no limitations are expected. To challenge the pumping system, its performance under a massive gas injection event, and hence under highly collisional operation conditions close to the cryopump is investigated. Also here, sufficient safety margin is found.

1. Introduction and background of the work

The JT-60SA device which is currently being built under the Broader Approach Satellite Tokamak Programme jointly by Europe and Japan, and under the Japanese national program, will start operation in 2019. One of the top research goals is to study high density plasma physics in view of a demonstration fusion power plant. This mission is clearly addressed in the JT-60SA Research Plan [1] which states: *The project mission of JT-60SA is to contribute to early realization of fusion energy by supporting the exploitation of ITER and by complementing ITER in resolving key physics and engineering issues for DEMO reactors.*

High plasma densities translate directly in high divertor and sub-divertor densities. But the effect of collisional flow and its influence on the particle exhaust function of a divertor and its pumping system has not sufficiently been addressed in past devices, when it was fully justified to neglect the collisions (e.g. in the ITER divertor development [2]). In this context, this paper presents an integrated modelling of the divertor pumping system of JT-60SA. This work is one of a number of activities carried out by the joint Japanese-EU JT-60SA Research Unit, with the EU team being organized in the framework of the EUROfusion WPSA work package, in close interaction with the F4E JT-60SA home team [3].

The operational window of the divertor is mainly given by power handling requirements limited by the material properties and exhaust requirements limited by the effective pumping speed performance of the vacuum system. Hence, the divertor has to reconcile key physics and technology functions in a sound way. This paper presents a generic integrated workflow to assess the operational window of the pumping system, which is then exemplified using JT-60SA in a challenging case for pumping, namely under the scenario #2 [1], with moderate plasma density but strong gas puffing.

2. Generic workflow for integrated modelling

The torus vessel throughput and composition (hydrogenic (fuel-type) and potential plasma enhancement gases) alone is not sufficient information to produce an appropriate integrated design of the particle exhaust system which comprises the divertor and its vacuum pumping system. On top of this has to come the information on the pressure distribution in the sub-divertor, and the density at the pump inlet via which this throughput has to be pumped. This requires the use of a neutral gas code which is able to calculate the flow field in the sub-divertor region. Here, it has to be considered that the effective pumping speed at the full divertor ring results from a balance of the pumping speed of (all) the distributed divertor vacuum pumps (connected with the subdivertor region of some divertors; other divertors are linked to these via toroidal slots) and the recycle fluxes towards the plasma. Even today, to simulate such a system under consideration of all geometry details and through all collisionality regimes, is beyond the computational state-of-the-art. This is why we suggest in this paper a two-stage approach [4].

The logical first step is a zeroth order sensitivity study to identify the most relevant flow paths of the problem aiming for some sort of simplification and to identify the simplified domain for the following detailed analysis. For this purpose, this work uses the flow network tool ITERVAC [5], which estimates the recycled flow rates and the pumped flow rates together with the related flow paths. It is estimative only, because it models the plasma as black hole and represents the collisional flow via generalized equations. However, it provides valuable input to find the geometry elements which govern the flow pattern and to separate them from the ones which can be neglected in the next stage of the treatment. Finally, it illustrates if a 2D assessment is sufficiently representative to characterize the flow pattern, or if one has to go for a 3D treatment. The next step is then to do a more accurate treatment of the sub-divertor neutral gas flow using a collision-free approach (such as NEUT2D [6]), a simplified collisional approach (EIRENE [7]) or a complete collisional approach (DIVGAS [8]). At this level, the simplified treatment of the plasma as black hole is being dropped, and the boundary is described with ´real´ particle flux and temperature profiles along the upper divertor region. This information is typical output from a plasma edge code (such as SONIC or SOLPS). Towards the pump side, a capture coefficient is introduced which translates the pumping speed of the installed pumps together with the conductance limiting effect of any port or duct geometry upstream the pump inlet into an effective pumping speed at the edge of the sub-divertor computational domain. It is this assessment which links the engineering design of the pumps with the particle exhaust function of the divertor. Parametric variations of the capture coefficient or the location of the pumping gap allow to optimize the integral divertor pumping system.

In the following, it is shown how this workflow is applied to the JT-60SA scenario # 2 [9], where the particle handling needs to be fulfilled at full injection of power of 41 MW for pulses of 100 s (high-particle loads). A full ITERVAC analysis is being done to find the most feasible way to simplify the sub-divertor and identify the most feasible computational domain for the next step. A neutral flow simulation was then performed on the basis of SONIC results as boundary conditions. The sub-divertor flow calculations have been done under consideration of intermolecular collisions using the DIVGAS code. Finally, the cryopumps are characterized for a particularly challenging operational case, namely a massive gas injection (MGI) event. This allows to explore the operational window of the JT-60SA divertor pumping system further.

3. JT-60SA divertor pumping system configuration

The JT-60SA device is capable of confining high-temperature deuterium plasmas lasting for a duration of typically 100 s. During this time interval, the exhaust gas has to be extracted via the divertor system, where a toroidal cryogenic pump will perform the particle removal, see Fig. 1. The cryogenic pump consists of nine 40° modules, each of which is individually connected to a cryoline. There are three cryolines, which supply maximum two, three or four modules, respectively. By different valve settings, this allows four seven different operational configurations with the pumping speed being varied in steps between 22% (2 modules connected) and 100% (all nine connected). The cryopump modules feature two thermal shield systems (there is a water-cooled chevron baffle integrated in the cassette body and an 80 K cooled shield system). The actual hydrogen pumping cryocondensation surfaces are circular pipes (design recently changed) supplied with 3.7 K sub-cooled liquid helium.

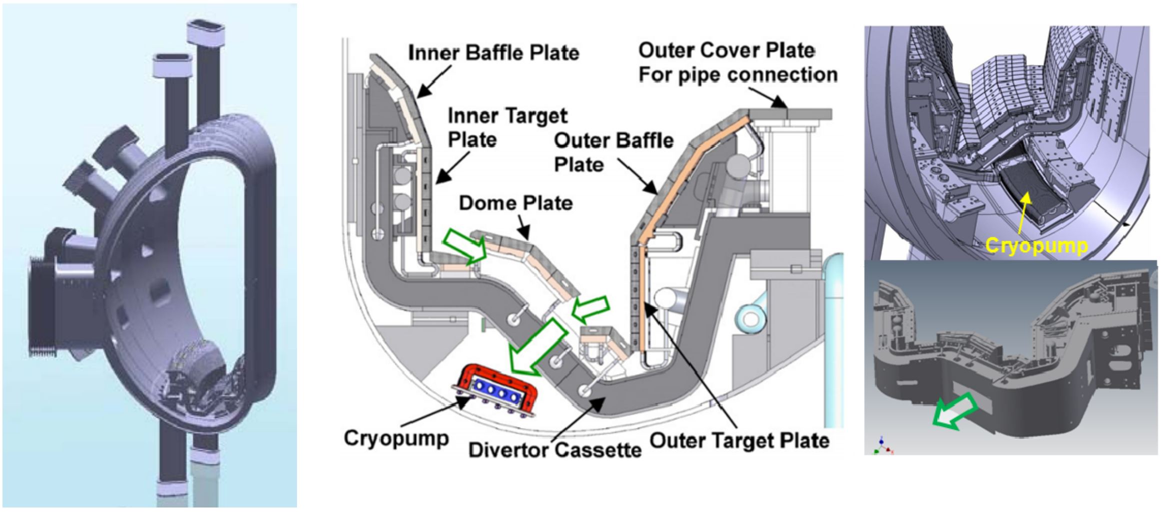

FIG. 1. Illustration of the JT-60SA divertor pumping system. Left: Full 40° sector model. Middle: 2D cut highlighting the cassette design with integrated cryopum. Right: 3D illustration of the installation situation. The dominant path of the torus gas exhaust towards the cryogenic pump is denoted by the green arrows.

4. ITERVAC analysis

The first step in such an analysis is a sensitivity and simplification study of the CAD model so as to identify these flow paths in the cassette and pump system geometry which contribute the most to the overall performance. The gas passages through the divertor cassettes can be simulated as a 2D network of channels with a known conductance. For the simulations, the ITERVAC code is used, which covers all flow regimes from laminar flow to the molecular flow regime; as the name is indicating, it was originally developed for the ITER divertor pumping system [10]. ITERVAC is an engineering model code for complex vacuum systems which represents the flow system as a network of channels with a predefined shape and length connected by nodes for mass flow balancing. Main parameters for the simulations are gas type, temperature, inlet and pump pressures and pumping speeds of the pumps. The results are the pressure differences and related gas throughput for every channel. The network approach is able to break down a 3D geometry (as is the case for the divertor pumping system) to a 2D network, if the channels are chosen properly.

Fig. 2 is illustrating the installation situation of a divertor cassette in the vessel with the different flow paths (red arrows), together with the final 18-channel ITERVAC model ([11]).

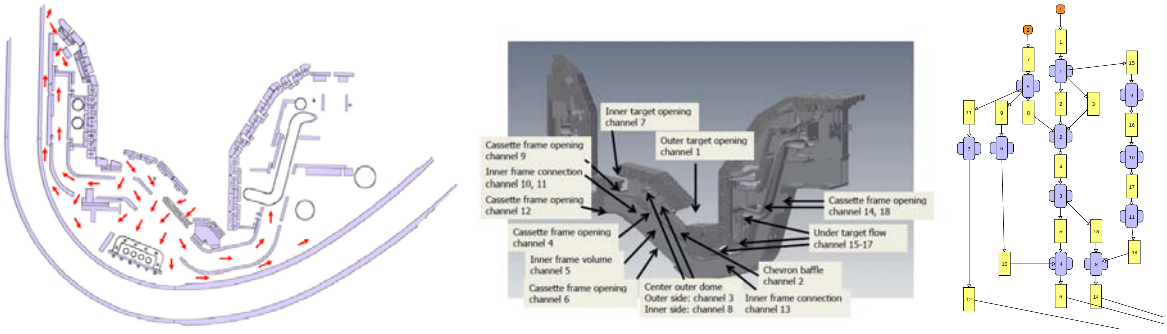

FIG. 2. Delineation of the ITERVAC flow pattern of the JT-60SA divertor pumping system (right) from the CAD model (left). The yellow structures in the ITERVAC model represent channels equivalent to the flow paths, the blue structures are nodes between the channels, and the two red points represent openings towards the plasma.

A typical output is plotted in the following Fig. 3. It shows the effective pumping speed at a nominal pumping speed of 100 m³/s (the JT-60SA baseline reference value). The figure illustrates that due to conductance losses, in free molecular flow regime, only 73% of the nominal value are accessible. However, at increasing divertor pressures, the effective pumping speed increases (here, it is always assumed that the cryotemperatures can be maintained), and at pressures of ~1 Pa, the losses are compensated. For higher pressures, the effective pumping speed does even increase beyond the reference value. This analysis gives a zeroth order understanding and demonstrates the overall feasibility of the system.

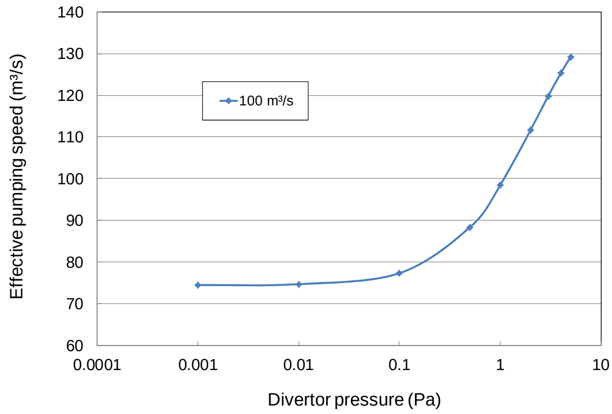

FIG. 3. Integral divertor pumping performance for a nominal cryopump pumping speed of 100 m³/s.

As last step at this analysis level, a most representative simplification of the CAD model in preparation of the next step was done, as shown in Fig. 4. The found final domain will now be used to do a self-consistent transport simulation of neutral gas. Compared to Fig. 2, it is much simplified, but based on ITERVAC checks, the final domain performs within ±20% as the ITERVAC model, so that representativity is ensured.

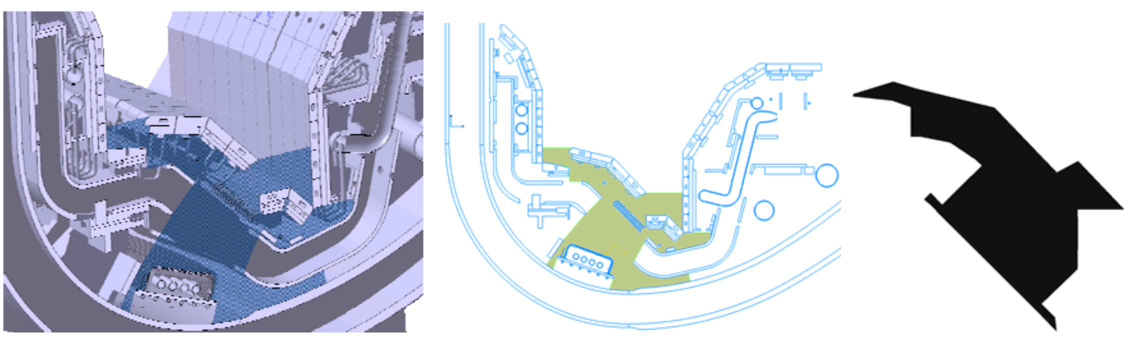

FIG. 4. Definition of the simplified final computational domain (right) from the CAD model (left). It has to be noted that the domain contains the water-cooled chevron baffle.

5. DIVGAS analysis

5.1. Domain and boundary conditions

At this level, the simplified treatment of the plasma as black hole is being dropped, and the boundary is described with ´real´ particle flux and temperature profiles along the upper divertor region. Towards the pump side, a capture coefficient is introduced which translates the pumping speed of the installed pumps together with the conductance limiting effect of the port and its installations into an effective pumping speed at the edge of the sub-divertor computational domain.

Previous works [6, 12] on neutral transport modelling of JT-60U particle exhaust were based on the interaction between neutral gas and plasma particles. Therefore, processes such as ionization by electrons, charge exchange and elastic collisions have been included in the description of particle transport in the aforementioned studies. However, neutral-neutral interaction has not been yet addressed in JT-60SA particle exhaust studies before. Consequently, one requires an additional tool that is able to describe the 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 [13]. 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 [14]. Furthermore, it has been applied to the ITER divertor system [15]. And most of all, a detailed benchmark against NEUT2D, although limited to the collisionless regime, has been conducted successfully for JT-60SA [16]. DIVGAS has also become the reference code for the integrated development of the DEMO divertor system in EU [17, 18].

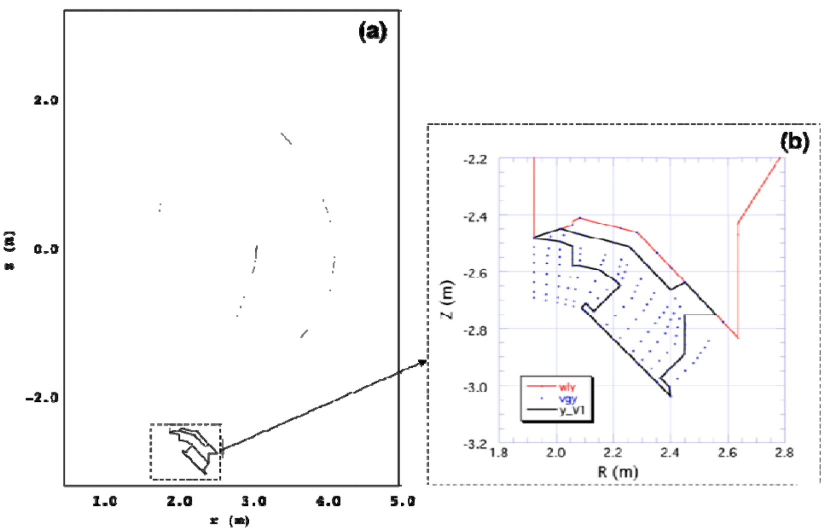

FIG. 5. The JT-60SA grid: plasma, plasma-vacuum region, vessel, divertor und sub-divertor region. Sub-divertor region is enclosed in the dashed box. The zoomed area shows the discretization of sub-divertor region: the points are the cell centers and the physical boundary is denoted in bold black line.

Fig. 5 is showing the JT-60SA grid with the sub-divertor domain considered as derived in section 3 above. In this figure, the physical domain of the sub-divertor has been discretized into cells.

The presence of the neutrals coming from the private region and divertor targets towards the sub-divertor has to be introduced by a proper choice of boundary conditions. The interfaces between plasma vessel and sub-divertor were chosen as the left- and right-most slots located in between the divertor dome and inner- and outer-target plates, respectively. A dedicated SONIC calculation was specifically performed for this task in order to set the BCs in the sub-divertor interfaces via given profiles of influx, speed and temperature. The found boundary conditions to be applied in the DSMC simulations read: the deuterium molecule influx to the sub-divertor was found at particle rates of 1.56×10^{23} part/s (Gate 1) and 2.95×10^{23} part/s (Gate 2). The particles have a flow speed of 314.3 m/s (Gate 1) and 589 m/s (Gate 2). The translational temperatures of the particles at Gate 1and 2 are 1118.57 K and 1335.67 K, respectively. Last but not least, the pumping surface located at the bottom part of the physical domain will absorb the particles with a certain capture coefficient (ratio of absorbed to incoming flux at surface). The capture coefficient at the pumping surface is set to 3% of the total incoming flux. The rest 97% is reflected back to the sub-divertor domain with a cosine distribution at a temperature of 293.16 K. As particle-wall interaction model, in the three approaches the D2 molecules are diffusely reflected from the sub-divertor walls at a temperature of Tw = 293.16 K.

5.2. Typical results

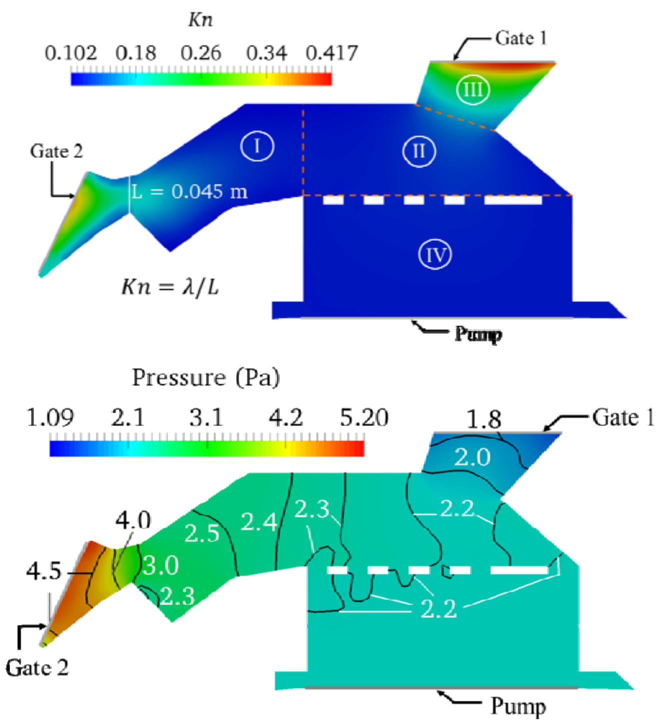

FIG. 6. Results of the DIVGAS simulations. Top: Calculated Kn number contour plot indicating that transitional flow regime prevails. Bottom: calculated pressure contour plot.

Fig. 6 is indicating two typical outputs of a DIVGAS analysis. The top figure is illustrating the sub-divertor collisionality in terms of the calculated Kn number. Such a plot can only be done with a code that considers collisions (the collision-free case results in a Kn number of infinity). It is known that the influence of collisions can be neglected only in the region Kn > 10, whereas in our case we find the Kn number to be below 0.5 in the whole sub-divertor area. This implies the transitional flow regime is found, which is defined for Kn values between 0.1 up to 10, where neither a free collisional nor a continuum approach are sufficient to describe the flow dynamics. This justifies strongly the necessity to consider collisions, if one needs to have a physically correct description of the flow in this system (see [16] for a detailed discussion and comparison with corresponding collisionless cases).

The pressure contour plot reveals a value of about 2.2 Pa in front of the pumping surface, whereas only 1.3 Pa was found in the hypothetical collisionless case [16]. The JT-60SA reference case is specified with a fuelling rate of 100 Pam³/s (average; 300 Pam³/s peak over 5s max) [1]. Together with the found 2.2 Pa, this translates into a pumping speed requirement of 45 m³/s. This value is below the curve shown in Fig. 3, for any range of rarefaction. This shows that the design of the pumping system for scenario #2 is sound. However, the existence of transitional flow conditions at the pump inlet region (Kn ~ 0.1) means additional heat loads to the cryoplant.

6. Pumping system challenge: MGI event

JT-60SA will face the problem of disruptions. Rapid and massive injection of particles into the plasma is one of a variety of different proposed concepts to safely terminate disrupting plasma. More investigations are needed to prove the suitability of disruption mitigation systems and to find the best candidate technology (valves, injectors) and gases. In principle, the foreseen injected quantities of material may be large enough to have significant implications on the operation of the divertor pumping system. The pressure jump and high mass flows in the vacuum system after a MGI event will result in high heat fluxes to the cryopumps. Consequently, the temperatures of the cryosurfaces increase. If the temperature of the condensation surfaces increase above the saturation temperature, the pump is not pumping anymore and goes into regeneration. The saturated vapour temperature for H_2 and D_2 are close to the cryopump nominal operation conditions. Hence, there is a risk that the cryopumps go into spontaneous regeneration and large quantities of gases have to be regenerated and processed by the roughing and regeneration pumping system. It was therefore tried to make a worst case parameter study in order to find the operational limits of the existing divertor pumping system.

In this study we used a transient thermohydraulic code which was developed for a similar assessment of the MGI situation in ITER [19] and re-worked for the JT-60SA pumping system geometry. As the type of gas is still under discussion, we performed calculations for H_2, D_2, Ne and Ar. With regard to the injected amounts, 400 Pam³ seems to be good number (scaled from JET), but we varied up to 4000 Pam³, the latter is of the order of the explosion limit if the injected gas would be hydrogenic. The properties of the cryosystem, in particular heat loads were taken from the valid PID document [20].

In all calculated cases, the cryopump could recover to normal operation quickly after a MGI event and did not get into spontaneous regeneration. Even under the worst cases, regular pumping was provided again after 50 s, although in the first few seconds after the gas injection, heat loads to the pump were increased up to factor 4.

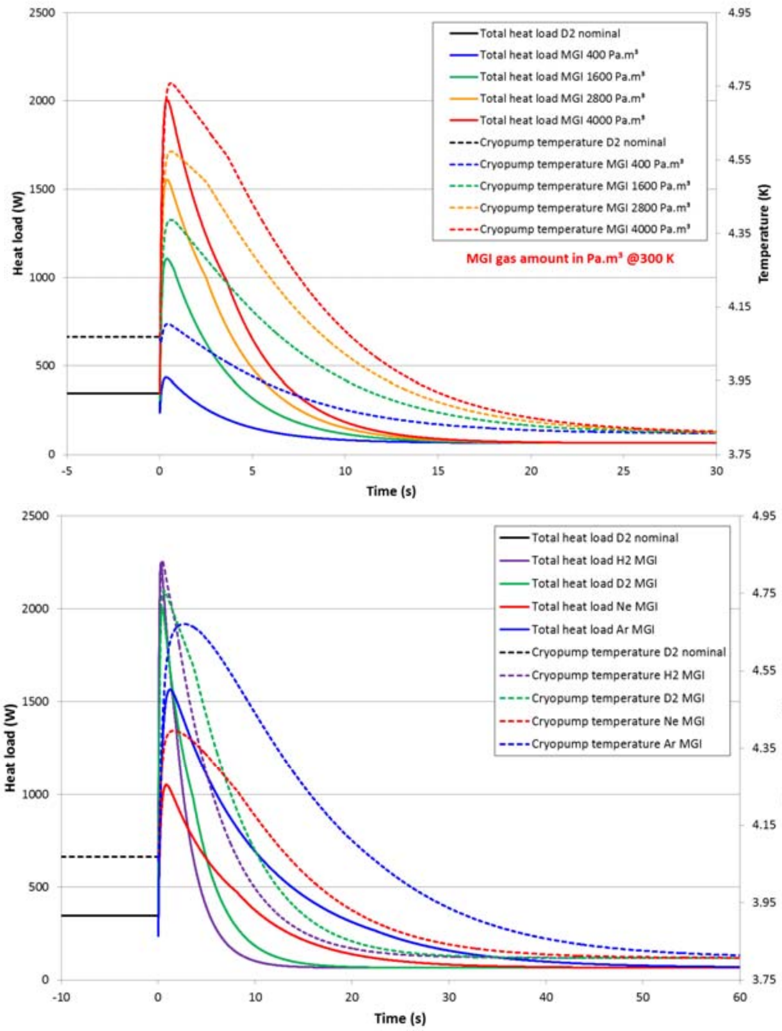

FIG. 7. Resulting heat loads and temperatures of the JT-60SA cryopumping system after a MGI event. Top: Variation of injected amounts of D_2. Bottom: Injection of various gases at 4000 Pam³.

7. Conclusions

The JT-60SA divertor pumping system was investigated using an integrated approach, which combines plasma physics information (chosen boundary conditions along the sub-divertor-plasma interface taken from a SONIC run) and vacuum pumping information (capture coefficient). It was found that for the studied example (Scenario # 2), the pumping system is performing well. Even in the case of a very challenging MGI event, no issues were found with the operation of the vacuum pumping system.

The simulations in the sub-divertor region revealed clearly that collisions have to be considered in the sub-divertor domain. It was also found that the two-stage approach (ITERVAC + DIVGAS) is able to provide helpful answers and estimations. It is therefore suggested to treat the other JT-60SA scenarios according to the same approach, in particular the high density scenario #3.

Acknowledgements

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