# Characterization of gas flow in the JET sub-divertor

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Quantifying the gas flow of hydrogenic gases in vacuum conditions (no plasma) is a critical model calibration step in computational plasma edge physics, for providing accurate pumping speed in geometrically reduced 2D model configurations, and for plasma density control in existing and future nuclear fusion devices. The focus of this work is on assessing the effective pumping speed of the Joint European Torus (JET) vessel (figure 1) based on in-situ pressure measurements as well as through time-dependent EIRENE [1] simulations using an axisymmetric vessel geometry. The simulated main chamber and sub-divertor gas pressure is compared to measurements in gas-into-empty-vessel experiments. The primary purpose of such comparison is to determine vacuum conductances in the JET vacuum vessel and the 2D effective pumping speeds of the divertor and neutral-beam cryogenic pumps, and the vessel turbomolecular pumps.

The pressure measurements of Baratron and Penning gauges in JET dry-runs were used to derive a unified approximation of the pumping speed of the evacuated vessel. Conductance-based Baratron gauges measure pressures in the range of $5x10^{-3}$ Pa to $1x10^{1}$ Pa and are located at the bottom of the sub-divertor. The Penning gauges located at the bottom of the sub-divertor and the outer vessel midplane, based on the principle of cold-cathode ionization, measure pressures from $1x10^{-7}$ Pa to $1x10^{-1}$ Pa.

The effective pumping speed of a vacuum system depends on the nominal speed of the pump and conductance of the vessel structure. We compare the effective pumping speeds of the measurements in the actual 3D vessel geometry to the pumping speeds of the time-dependent 2D (toroidally symmetric) simulations by calculating the time constant of the decay when gas

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[ii] *See the author list of "Overview of T and D-T results in JET with ITER-like wall" by C. F. Maggi et al. Nuclear Fusion 64 112012 10.1088/1741-4326/ad3e16*

is being pumped out of the system. By dividing the vessel volume (approximated at 200 $m^3$) by the time constant, the effective pumping speed of the vessel is obtained. This effective pumping speed of the JET vessel was measured by Obert et al [2] to be 200 $m^3$/s while engaging the divertor cryo-pumps and the turbomolecular pumps.

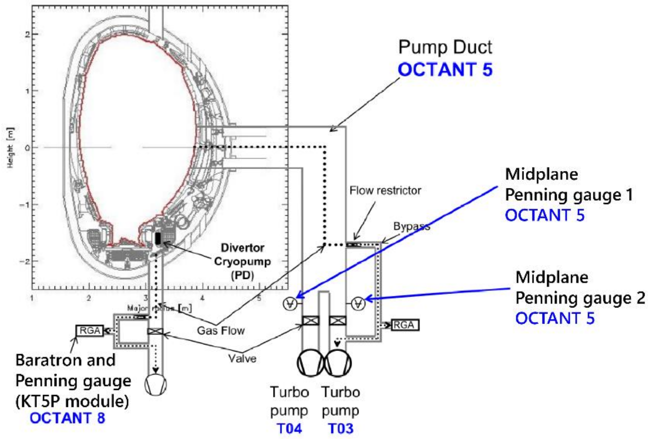


Figure 1: JET schematic of the pressure gauges located in the sub-divertor and the midplane pump duct [3].

The neutral gas transport code EIRENE is applied to simulate the gas injection and pump out in time-dependent mode to assess the pressure distribution and time response of the simplified, axisymmetric JET vessel. The code solves non-stationary linear and non-linear kinetic transport equations to simulate the transport of gas self-consistently in vacuum systems and plasma domains. The simulation environment includes a toroidally symmetric injection surface at the top of the vessel and a toroidally symmetric pumping surface where the sub-divertor cryopump is located. The structural elements are set at a static temperature of 300 K, and the pump surface is set to 10 K to replicate the conditions of super-critical helium (as in [2]).

In low pressure conditions in JET, i.e., for pressures lower than 7.0 mPa (sub-divertor) and 0.16 mPa (main chamber), corresponding to characteristic lengths of 0.04 m (sub-divertor) and 1.8 m (main chamber), the flow is free-molecular (Knudsen number > 10). For pressures higher than 7.0 mPa and 0.16 mPa in the sub-divertor and the main chamber respectively, the non-linear Bhatnagar-Gross-Krook (BGK) approximation should be applied to account for inter-molecular interaction observed in viscous flow conditions.

Assuming the divertor cryo-pump sticking coefficients are between zero (no pumping) and unity (100% pumping) in the simulation, the pumping speed of $D_2$ molecules ranges from 100 $m^3$/s to 250 $m^3$/s. Based on the sticking coefficient of the divertor cryo-pump, the molecules in contact with the pump are either absorbed or reflected. The simulated pump out times measured in three different locations around the 2D vessel are the same, which indicates that the conductance between the pump and other regions of the vessel does not affect the effective pumping speed.

Comparing collisionless simulations of different species of hydrogen, we see that the pumping speeds of the isotopes scale with the square root of the isotope mass and the isotope specific sticking coefficient of the pump surface. Based on previous studies by Day et al [4], the isotope specific sticking coefficients are 0.6 for $H_2$, 0.9 for $D_2$ and 1.0 for $T_2$. Considering the different sticking coefficients of each isotope, the resulting pumping speeds are 319 $m^3/s$ for $H_2$, 236 $m^3/s$ for $D_2$ and 194 $m^3/s$ for $T_2$ (figure 2).

With an assumed sticking coefficient of 0.90, the simulated effective pumping speed for $D_2$ is 240 $m^3/s$, which is higher than the assumed 200 $m^3/s$ nominal pumping speed for the cryo-pump. A potential cause for this difference is that the simulated divertor cryo-pump has a larger surface area than its real 3D toroidally non-symmetric counterpart. Further studies aim to find better parameters for the divertor cryo-pump, with the addition of the NBI cryo-pump and turbomolecular pump surfaces in 2D edge plasma simulations coupled to EIRENE for the neutral gas flows in the poloidal plane, while including the intermolecular interactions.

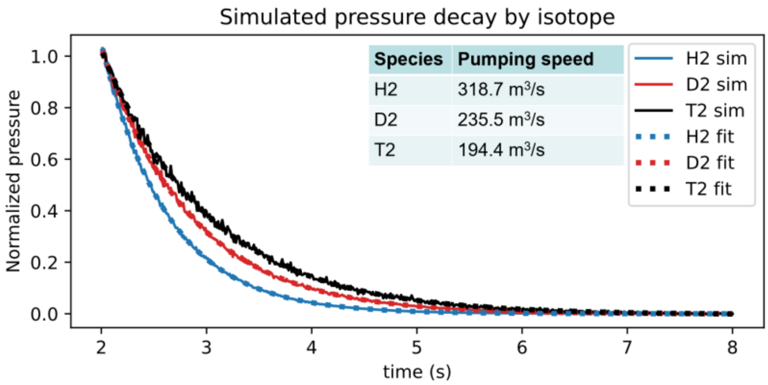


Figure 2: Simulated pressure decay comparison of the hydrogenic species with normalized fits used to calculate their respective pumping speeds.

By comparing pumping speeds of the Baratron and Penning gauges for separate pulses shows that the gauges are consistent between pulses with the same pump configurations, but inconsistent when compared to one another. For a gas injection to an evacuated vessel with the sub-divertor and NBI cryo-pumps at super-critical helium temperatures, the Penning gauge located in the lower sub-divertor records a pumping speed of 95 $m^3/s$, whereas the Penning gauge on outer midplane records 180 $m^3/s$ and the Baratron in the lower sub-divertor records 137 $m^3/s$. A root cause for the differences in pumping speeds between the simulation and the measurement are hypothesized to be caused by the assumed axisymmetric geometry of the simulation versus the actual 3D, and the lack of intermolecular interaction in the simulation.

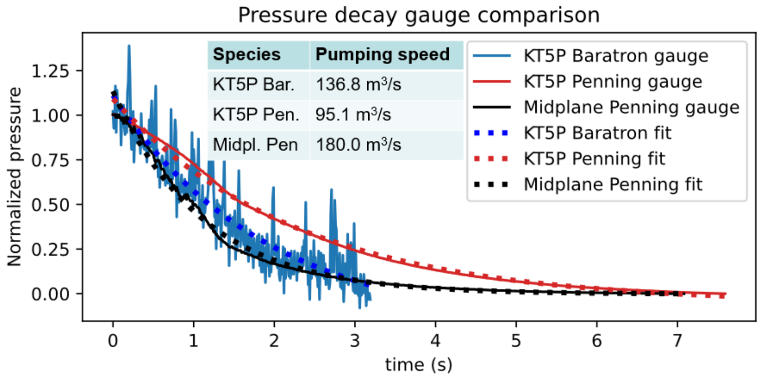


Figure 3: Measured pressure decay comparison of the Baratron and Penning gauges with normalized fits used to calculate their respective pumping speeds.

Measured effective pumping speed of the JET vessel with active divertor cryopumps, NBI cryo-pumps and turbomolecular pumps were 137 $m^3/s$ for the sub-divertor Baratron, 95 $m^3/s$ for the sub-divertor Penning gauge and 180 $m^3/s$ for the mid-plane Penning gauge (figure 3). The uncertainties of these values are due to the differences between the gauge mechanisms and their locations. However, all the experimental pumping speeds are lower than the historical measured value of 200 $m^3/s$ [2], which suggests decreased gas conductance. A potential reason for the decreased conductance is the changed divertor structure and the addition of louvres, which are designed to protect the divertor cryo-pump from incoming radiation. In comparison, the conductance of the AUG sub-divertor is measured to be 134 $m^3/s$ [5], which is close to the lower end of the experimental conductances.

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