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## ABSTRACT

Vacuum systems of neutral beam injectors have very demanding requirements in terms of pumping speed, throughput, and capacity. Due to their high affinity to hydrogenic species, porous sintered Non-Evaporable Getters (NEG) are a possible candidate for deployment in giant hydrogen ion sources and neutral beam injectors for fusion. This paper presents the numerical interpretation of experimental tests on a recently developed NEG cartridge, that is part of a modular pump under development for neutral beam injectors. The cartridge is composed of six stacks of ZAO® porous sintered NEG disks and a heater. It was tested under hydrogen loads relevant for neutral beam injectors, namely, at constant pressure or constant flow, such that the hydrogen pressure was in the range of 20 mPa–40 mPa. The result of the sorption test was reproduced by a three dimensional flow simulation in molecular regime to determine the actual pumping speed, the effective sticking coefficient, and the uniformity of the gas load on the various NEG disks. The procedure developed and the results obtained provide the basic understanding for interpreting the large-scale tests on the modular pump, consisting of 34 of these cartridges.



## I. INTRODUCTION

Neutral beam injectors (NBIs) for fusion[1] have the need for vacuum systems with an installed pumping speed of several millions of liters per second in hydrogen.[2] Non-Evaporable Getter (NEG) technology shows a high affinity toward hydrogen and its isotopes; therefore, it is a potential candidate for the pumping system for future neutral beam injector applications. In recent years, significant steps forward have been made in the NEG field, with the development of sintered pumping elements based on the ZAO[3] alloy. Commercially available NEG pumps have the scale of some cubic meters per second in hydrogen.[4] For this reason, in the framework of the R&D activities for the EUROfusion DEMO plant,[5] NEG technology is being investigated in strong collaboration with the industry. A milestone in the development program is the demonstration of NEG pump technology by realizing a modular pump mock-up of relatively large scale[6] and testing it under vacuum conditions relevant to neutral beam injectors in the TIMO facility at KIT Karlsruhe.[7] The NEG pump mock-up consists of 34 cartridges, each one composed of 6 stacks with 44 ZAO porous sintered NEG disks, for a total amount of 264 disks, and the heater element.

Numerical models able to simulate the pumping behavior of a large NEG pump are necessary in order to estimate the gas distribution inside an NBI. In this paper, a first approach in this direction is shown.

A model of the single cartridge has been developed in order to reproduce sorption tests performed at SAES Getters laboratories. The cartridge represents the base unit which constitutes the large NEG pump mock-up. After that, the detailed model has been simplified in order to obtain a reliable model solvable with less computational effort.

## II. ABSORPTION TESTS ON NEG CARTRIDGE

The NEG cartridge has the geometrical shape of a prism with a height of 150 mm and hexagonal base with a long diagonal of 100 mm. The cartridge has been installed for the tests in a vacuum chamber with a volume of 0.06 $m^3$.

Absorption tests at a pressure of 0.02 Pa for hydrogen have been performed according to the ASTM F798-97 standard practice. The experimental procedure is based on the known conductance method and it is performed maintaining a constant pressure inside the vacuum chamber of the test bench. The injected gas flows into the vacuum chamber through a known conductance, and the pressure in the chamber is maintained constant regulating the gas flow by means of a control valve. The use of turbo-molecular pump is necessary in order to pump inert gas species. The pressure is measured by using the Bayard–Alpert gauge. The pumping speed of the NEG cartridge is calculated by applying the pumping equation to the system.

The tests have been performed at two different temperatures of the NEG cartridge (see Fig. 1). The pumping speed measured at higher temperature is larger and more stable with respect to the adsorbed gas quantity.

## III. GAS FLOW SIMULATIONS

Three different points of the experimental curve at 25 °C have been selected and analyzed by 3D gas flow simulations using the AVOCADO code.[8,9] The code makes use of the mathematical analogy existing between the law of molecular flow and radiative exchange between surfaces. The set of governing equations is derived on the basis of the fact that the geometry dominates molecular flow and that the pressure distribution is obtainable by surface discretization and calculation of mutual exchanges due to molecular trajectories.

The simulations have been performed in order to study the effective sticking coefficient and to investigate the non-uniformity of gas distribution on the NEG material because the experimental test can measure only the effective pumping speed at the point where the pressure gauge is installed.

FIG. 2. Isometric view of the CAD model of the experimental test bench.

The effective sticking coefficient is calculated as the ratio between particles' flux absorbed by the pumping surfaces and the collision frequency on the same surfaces. The effective pumping speed represents the pumping speed measured in the test chamber where the pressure gauge is installed.

The experimental points have been simulated setting the corresponding gas throughput ($Q_{in}$) injected in the chamber and the pumping speed ($S_{NEG}$) at the pumping surfaces of the NEG cartridge (see Figs. 2 and 3).

The pressure calculated on the surface, which represents the pressure gauge, was compared with the value measured during the reference test. Iteratively, the model runs changing the imposed $S_{NEG}$ until the calculated pressure matches the reference measured value. The NEG pump has been simulated by using three models, as shown in Fig. 4. In the *hexagonal model*, only the lateral surfaces of the prism pump gas, whereas in the second model, the gas is pumped by the lateral surface of cylinders representing the disks stacks. The

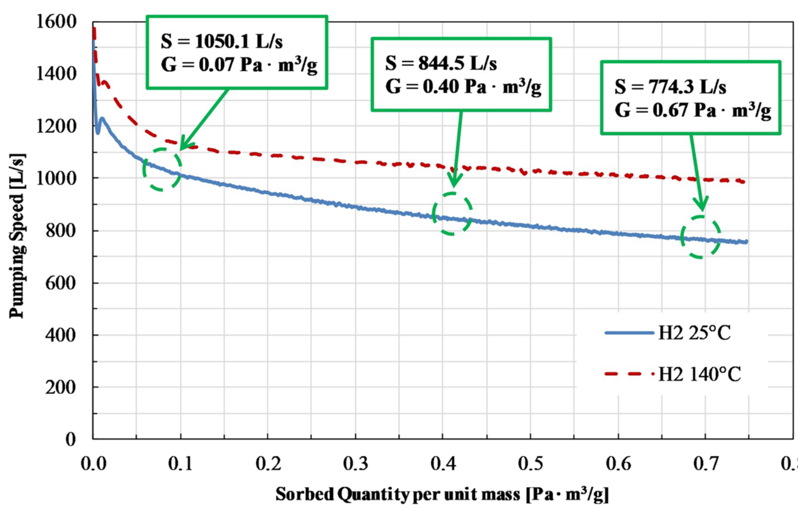


FIG. 1. Absorption tests at the constant pressure of 0.02 Pa performed on the NEG cartridge assembled with 264 disks at two different temperatures. The dashed green circles identify the experimental points selected for the simulations.

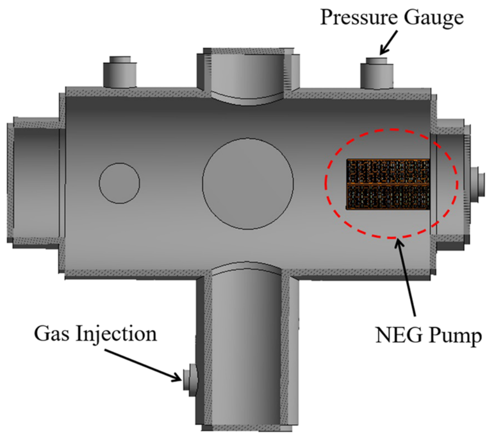


**FIG. 3**. Sectional view of the CAD model of the experimental test bench with the NEG cartridge installed.

model with the disks represents the real geometry of the pump (see Fig. 5).

The use of models with different details is useful to understand how to simulate large-scale pumps where the number of disks is so large that the computational time required to simulated pumps with all the details would be huge.

## A. Effective sticking coefficients

The effective sticking coefficients have been estimated using the pumping speed values reported in Table I.

At the concentration of 0.07 Pa m$^3$/g, the $S_{NEG}$ set with the *hexagonal model* is 5% higher than the one measured during the test, whereas for the *disks model* is 37% higher (see Fig. 1). This means that the pumping speed installed is higher than that measured mainly due to the reciprocal shadowing effects between the disks.

The value of the effective sticking coefficient for the *disks model* is lower than the one of the other models (see Fig. 6). This coefficient represents for the *disks model* the accurate sticking coefficient of the ZAO material, whereas for the other models describes how the particles interact with the simplified geometries. Therefore, to simulate large-scale pumps, it is possible to use the *hexagonal model* to study the general performances, in order to reduce the computational time.

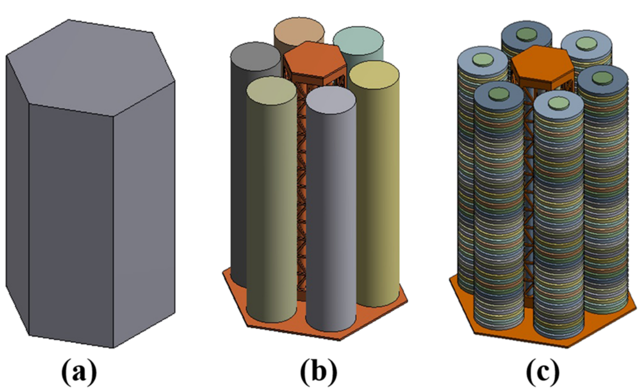


**FIG. 4**. NEG cartridge models: (a) *hexagonal*, (b) *cylinders*, and (c) *disks*. The models with cylinders and disks are shown without the external grid.

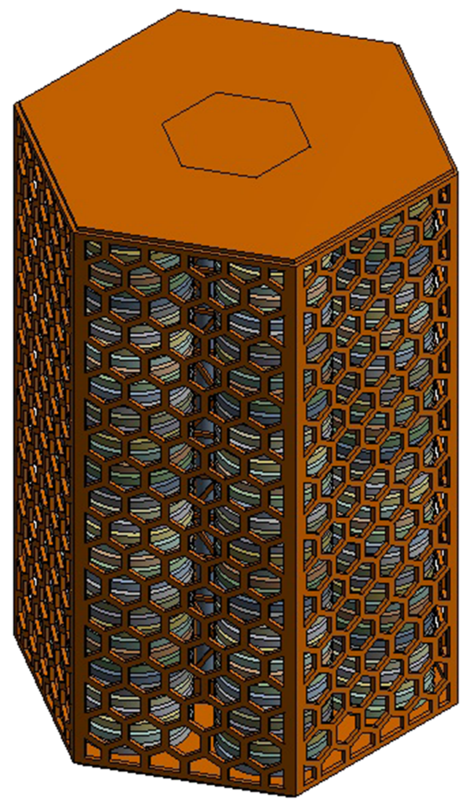

**FIG. 5**. View of the CAD model of the NEG cartridge.

Figure 7 shows the view of the *disks model* with the particles' flux absorbed estimated by the simulation. The variation in the vertical direction of the absorbed flux is very low, of about 1%. In the radial direction of each single stack, from the external grid to the heaters, the flux variation is about 16%, as shown in Fig. 8.

**TABLE I**. Pumping speeds set on the pumping surfaces of the models in order to obtain the same effective pumping speed in the test chamber.

| Model | Gas concentration (Pa m$^3$/g) | $S_{NEG}$ (L/s) |
|---|---|---|
| *Hexagonal* | 0.07 | 1112.7 |
| | 0.40 | 883.5 |
| | 0.67 | 808.2 |
| *Cylinders* | 0.07 | 1291.3 |
| | 0.40 | 997.8 |
| | 0.67 | 900.0 |
| *Disks* | 0.07 | 1435.6 |
| | 0.40 | 1078.6 |
| | 0.67 | 967.8 |

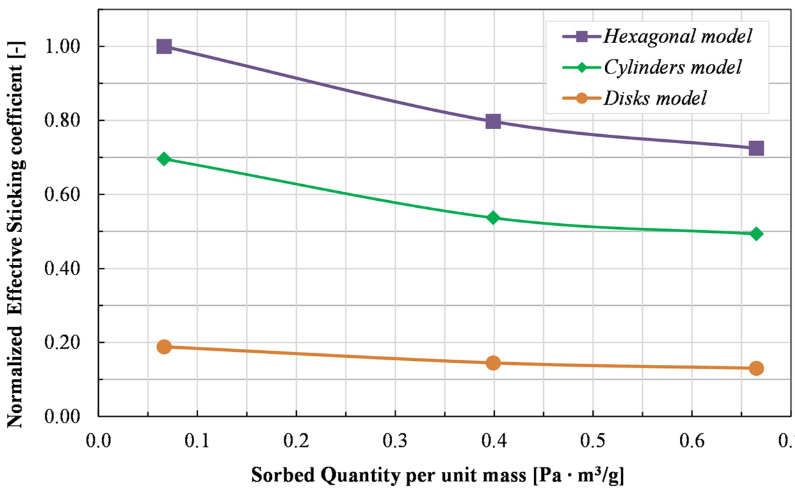


FIG. 6. Normalized sticking coefficients estimated by the simulations. The results have been normalized dividing by the maximum value.

## B. Particles' flux distribution

The particles' flux distribution has been studied considering the *disks model* using the same boundary conditions for both the models with and without the external grid. Table II reports the simulation settings with the corresponding results.

The pressure in the chamber calculated with both the models differs by less than 5%. Comparing the results of the two models gives an estimate of the conductance of the external grid, which is 15.2 $m^3/s$ for hydrogen. This value of conductance is large compared to the pumping speed of the NEG cartridge, so its influence on the effective pumping speed is negligible.

The particles' flux has been divided in equal class intervals. The getter area fractions that receive a certain amount of flux have been counted in the corresponding class interval. The getter area collected in each interval has been divided by the total getter area in order to obtain the normalized getter area. The distribution of the particles' flux adsorbed by the getter as a function of the normalized getter surface is reported in Fig. 9, considering both the cases with and without the grid.

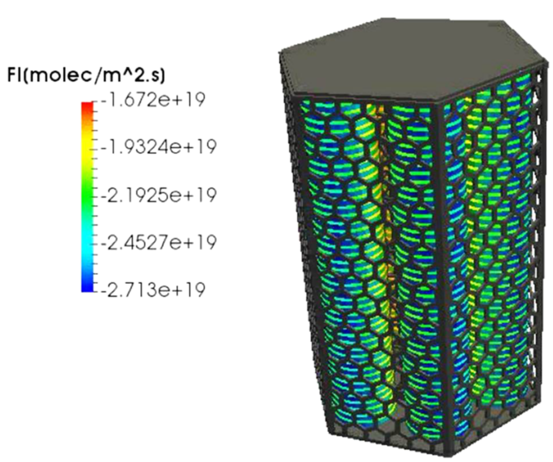


FIG. 7. View of the disks model cartridge with the external grid: particles' flux absorbed resulted from the simulations.

The effect of the grid is to make the flux distribution smoother, leading to softer transitions of particles' flux between different zones, which is useful to reduce the non-uniformities of gas concentration inside the material. The mean value of the flux

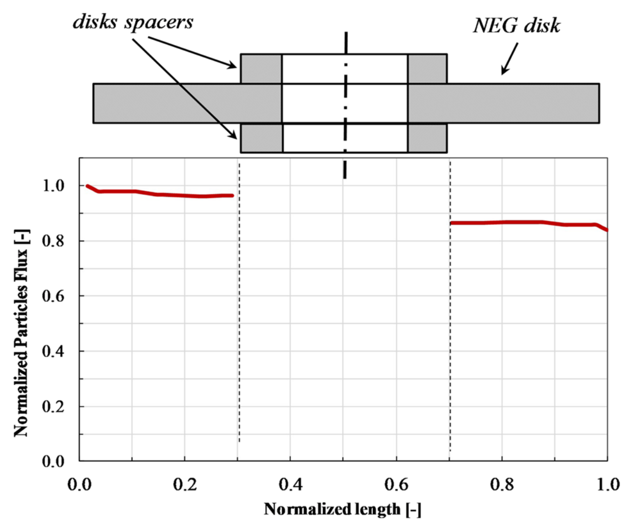


FIG. 8. Radial gradient of the normalized particles' flux absorbed by a disk in the stack as a function of the normalized dimension of the disk. The results have been normalized dividing by the maximum value (normalized length = 0: external side of the cartridge; normalized length = 1: internal side of the cartridge).

TABLE II. Pumping speeds set as the input of the code and chamber pressure calculated by the simulations of the *disks model* with and without the external grid.

| | | Chamber pressure (Pa) | |
|---|---|---|---|
| Gas concentration (Pa $m^3$/g) | $S_{NEG}$ (L/s) | with grid | without grid |
| 0.07 | 1435.6 | $2.00 \times 10^{-2}$ | $1.86 \times 10^{-2}$ |
| 0.40 | 1078.6 | $2.00 \times 10^{-2}$ | $1.89 \times 10^{-2}$ |
| 0.67 | 967.8 | $2.00 \times 10^{-2}$ | $1.90 \times 10^{-2}$ |

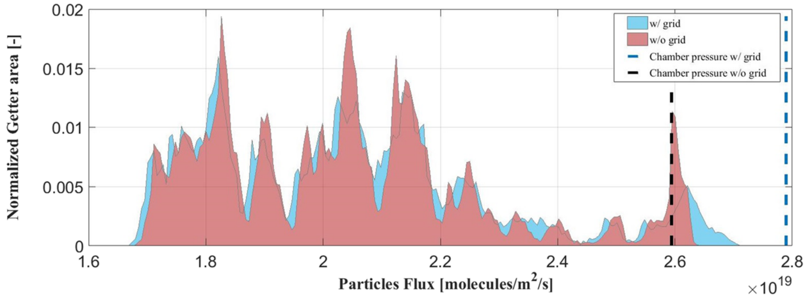


**FIG. 9**. Particles' flux distribution on the normalized getter surface of the *disks model* with and without the external cage for the simulated point at the gas concentration of 0.07 Pa $m^3$/g.

calculated for both the cases is of $2.04 \times 10^{19}$ molecules $m^{-2}$ $s^{-1}$, with a root mean square deviation of $2.41 \times 10^{18}$ molecules $m^{-2}$ $s^{-1}$ with the grid and $2.34 \times 10^{18}$ molecules $m^{-2}$ $s^{-1}$ without the grid.

The vertical dashed lines represent the pressure chamber for both the models reported as particles' flux according Eq. (1), where $F$ is the particles' flux (molecules $m^{-2}$ $s^{-1}$), $p_{chamber}$ is the pressure inside the chamber (Pa), $k_B$ is the Boltzmann's constant (J $K^{-1}$), $T$ is the particles' temperature (K), $m_{H_2}$ is the mass of the hydrogen molecule (kg), and s is the sticking coefficient,

$$F = \frac{p_{chamber}}{\sqrt{2\pi \cdot k_B \cdot T \cdot m_{H_2}}} \cdot s. \quad (1)$$

The line of the chamber pressure without the grid corresponds to the peak of area with the maximum adsorbed flux, whereas for the case with the grid, the chamber pressure does not intercept the flux value and this is an evidence of the shielding effect of the grid.

## IV. CONCLUSIONS

The adsorption test has been replicated by the numerical simulation with good results, using models with different levels of detail. The *disks model* is very detailed and it allows for studying the local behavior of the NEG pump, extrapolating the distribution of the particles' flux on the pumping surfaces, whereas the *hexagonal* and *cylinder models* allow for describing the global behavior of the pump. This more global description is useful to study large modular NEG pumps (such as the NEG pump mock-up), where a scaling approach is needed to reduce the computational effort.

## ACKNOWLEDGMENTS

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