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Conceptual design of scalable vacuum pump to validate sintered getter technology for future NBI application

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Non-evaporable getter (NEG) technology is a potential candidate as pumping system for future neutral beam injector applications. The strategy to validate the use of getter pump technology is based on the realization of a relatively large pump mock-up that has to be tested in fusion-relevant conditions. The objectives of this mock-up are to demonstrate that a pump of large dimensions and capacity is usable. This paper deals with the design of the mock-up, based on conceptual studies which involve at first 3D gas flow simulations considering different modular mock-up pumps based on NEG sintered disks. In addition transient thermal simulations with FE method have been performed with the aim to analyze the thermal response of the mock-up. The conceptual design has been carried out in order to define the best configuration to obtain high pumping speed with low spatial gradient of gas concentration inside the getter material. The suggested solution will exhibit a modular structure of getter disks, which on one hand simplifies the mechanical assembling, and on the other hand allows interpretative modelling at different scales. It is foreseen to test the pump mockup in the TIMO facility at KIT Karlsruhe.

Keywords: Neutral Beam Injector, Non-Evaporable Getter, Vacuum pump

1. Introduction

The vacuum systems of neutral beam injectors for fusion [1] have very demanding requirements in terms pumping speed and throughput [2] [3], with installed pumping speeds of several millions of liters per second in hydrogen. Due to its high affinity to hydrogenic species, non-evaporable getters (NEG) are a good candidate technology for the vacuum pumps deployed in neutral beam injectors [4], which require very large gas hydrogen throughputs in order to operate. Getter materials operate at room temperature, and their use could be particularly welcome in the absence of cryogenic supplies, if high temperature superconducting magnets are successfully deployed in future fusion plants. Commercially available NEG pumps have the scale of some cubic meters per second in H_2 (see for instance [5]).

In the framework of the R&D activities for the EUROfusion DEMO plant [6], 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 pump mock-up of relatively large scale, and testing it in vacuum conditions relevant to neutral beam injectors. The pump shall prove a good compromise between high pumping speed and capacity, with relatively stable performances over time.

Following the recent trends in the industrial practice, a highly modular design has been followed, with single getter elements consisting of highly porous sintered disks arranged in stacks, with a given spacing determined by the use of suitable washers. The getter material is specifically optimized for hydrogen sorption. The disk-based concept is extensively and reliably used in small scale pumps. The getters need to be heated up at temperatures in the range 450-650°C to be activated, i.e. recover their pumping properties after being passivated with reactive species (N_2, O_2, water, carbon oxides) and to be regenerated, i.e. extract hydrogen isotopes. In fact, exceeding a too high hydrogen concentration in the getter alloy would cause embrittlement of the sintered disk. As a consequence, the main design parameters for a getter-based pump are the geometric arrangement of the getter disks, and the arrangement of heating elements with respect to the getter disks (constituted by filaments of refractory metal). In addition, all the technical solutions used to heat up the getters – electrical connections, supports, high temperature insulators and support structure – shall be taken into account early in the conceptual design phase.

This paper reports the studies carried out to develop the conceptual design of the mock-up pump. The mock-up shall be representative, on a smaller scale, of the large scale system, and the experimental tests to be carried out on it shall provide benchmark results and prove the reliability of scaling laws and that analytical or numerical predictions related to its experimental behaviour (sorption, regeneration, thermal and electrical performance) are reliable. Having these goals in mind, three configurations were identified and studied.

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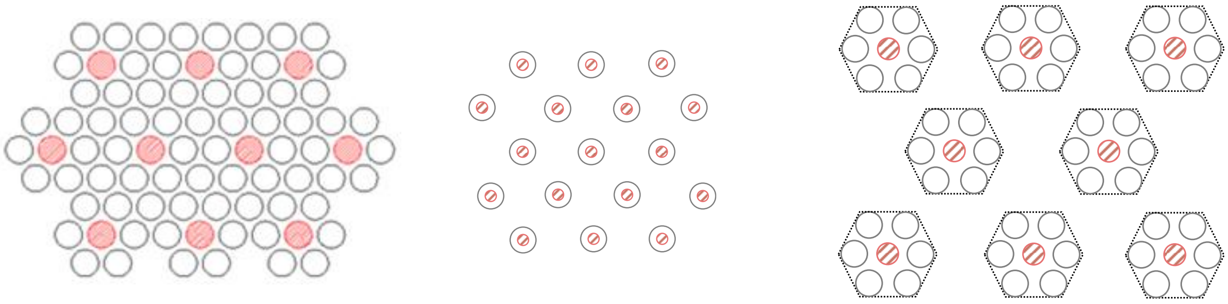

(a) (b) (c)

Fig. 1. Mock-up pump geometries studied (heaters red circles, stacks white circles): (a) Configuration 1, (b) Configuration 2, (c) Configuration 3

The three configurations differ in the spatial distribution of the stacks and in the installation position of the heaters respect to the stacks, as shown in figure 1[1]. The configurations have been compared on the basis of identical amount of getter material, with very minor differences due to the geometrical constraints needed to follow the stacks distribution scheme of each configuration.

Configuration 1 is compact, it has the stacks distributed in a uniform way with a honeycomb array; the heaters are installed outside the stacks. Configuration 2 has the heaters coaxial with the stacks, and the stacks placed with a uniform distribution which makes each stack independent from the other. Configuration 3 has a modular approach; six stacks are grouped in modules with hexagonal shape, the heaters are installed in the centre of the module external to the stacks.

A list of desired characteristics has been used to rank the three configurations, substantiating the design choices with more quantitative indications. The ranks were given on the basis of numerical simulations, in which the parameters were defined on the basis of experimental results on hydrogen and deuterium adsorption tests.

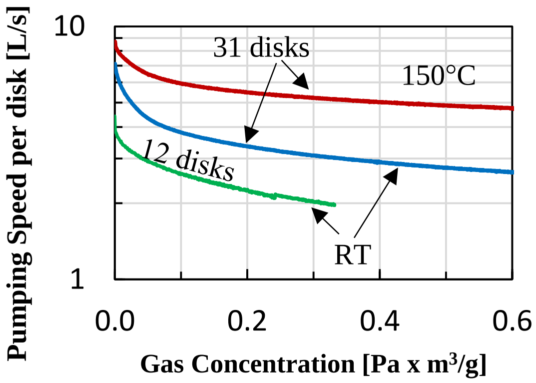

Fig. 2. Adsorbing tests on NEG disks with H_2: pumping speed scaled to a single disk as function of the gas sorbed per unit mass of getter

2. Adsorption tests on NEG disk stack

Adsorption tests have been performed following the ASTM F798-97 standard practice on two stacks, the first composed by 12 getter disks spaced of 0.5 mm and the second one formed by 31 disks spaced of 1 mm. The pressure in the test chamber was maintained at the constant value of 0.02 Pa. The pumping speed scales less than linearly with the number of disks due to the shadowing effects (Fig. 2).

3. Evaluation of three alternative configurations based on sintered getter disks

3.1. Impact on pumping speed and gas load uniformity

The gas flow regime in which the mock-up should operate is molecular (Knudsen number > 1), i.e. the macroscopic flow behaviour is mostly determined by collisions with solid walls and the effect of mutual particle collisions is negligible. The pumping performances of the three configurations have been analysed comparing the results obtained by numerical simulations performed using the AVOCADO code [7] [8].

In the models, the stacks of getter disks have been modelled as simple cylinders and placed inside a vacuum vessel which represents that one of the TIMO facility [9]. The system has been considered isothermal, at the temperature of 25°C. Being free molecular regime by hypothesis, an inlet pressure of deuterium gas of 1 Pa was chosen for simplicity. The pumping speed at the getter surface *S* has been converted in uniform pumping speed per unit area $\tilde{S}=S/A=21.4$ m s^{-1}. *S* was calculated by considering a pumping speed for single disk of 5 l s^{-1} and scaling this value to 9180 disks, while *A* is the total pumping surface of the cylinders representing the disk stacks in the model. The value of 5 l s^{-1} was obtained during the test on a stack with 12 disks reported in the Section 2. This value is not a reference, but a conservative value useful to fix an order of magnitude.

The throughput per unit area $\tilde{Q}$=Q/A is used as indication of the gas load uniformity. The results of the analyses (Fig. 3) show that in Configuration 1 $\tilde{Q}$ has a large variation, from 1.04 Pa m s^{-1} to 6.41 Pa m s^{-1}, with the stacks in the central zone all having the minimum value. In Configuration 2, a smoother variation of $\tilde{Q}$ is found, from 3.37 Pa m s^{-1} in the internal to 4.38 Pa m s^{-1} for the external zones. Configuration 3 has the same variation of specific throughput within each module, from 2.62 Pa m s^{-1} to 4.56 Pa m s^{-1}, so the pumping performance of the hexagonal getter module/cartridge does not depend on its position within the pump.

[1] All the configurations considered in the present study had been selected among some possible embodiments of the invention covered by the granted European patent EP316131 as well by corresponding Intellectual Property Right in the rest of the World.

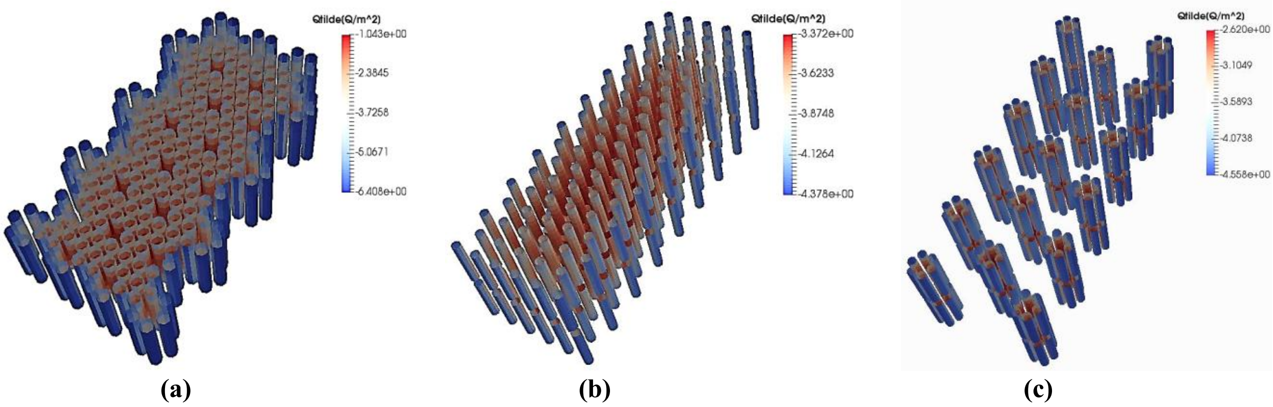

Fig. 3. Throughput per unit of pumping surface of the stacks: (a) Configuration 1, (b) Configuration 2, (c) Configuration 3

3.2. Uniformity of disk temperature during regeneration

The main goal of these simulations is to compare the thermal behaviour of the three configurations considering the geometry aspects and the heating system. Due to computational reasons, the geometries have been simplified and for the configurations 2 and 3 it has been considered only half mock-up taking advantage of the geometrical symmetry.

The analyses consider two phases in order to study the thermal aspects of the regeneration. In the heating up phase the heaters have been set with a fixed temperature T_h = 1060 °C and they exchange heat by radiation with the stacks and the ambient, which is at the constant temperature T_a = 50°C. The stacks have an initial temperature T_i = 50 °C. The cooling down phase studies the passive cooling of the stacks, which start from T_i that is the same reached at the end of the heating up phase and exchange heat by radiation with themselves and the ambient. The time simulated for both the phases is 7200 seconds.

The thermal response of the stacks changes if the they are located in the internal or in the external zones, so two groups of stacks have been chosen as reference for the results, one in the external zone and one in the internal one.

Analysing the heating phase (Fig. 4), the fastest transient is obtained with the configuration 2, while configuration 1 is the slowest. The temperature uniformity in configuration 1 is found to be quite poor, it varies from 600°C to 950°C in steady-state. Considering the cooling phase, configurations 2 and 3 have comparable characteristic time τ, whilst configuration 1 has larger τ; in the latter case the minimum and maximum temperatures among all getter stacks are quite different, about 100°C. For instance, one should notice that configuration 1 requires more than 1 h to cool down below 200°C, while the configurations 2 and 3 require only 30 min.

3.3. Technological aspects and constraints

The pump has to survive to thermal cycles and the adopted solution has to be compatible with remote handling. Metal and ceramic materials that are part of the pump have to be vacuum compatible. The thermal efficiency of the heaters and the temperature uniformity have an impact on the regeneration phase, in terms of duration and prevision of the residual gas inside the getter material. The reliability of the heating system is a fundamental aspect, as the failure of this system means the impossibility to regenerate the stacks.

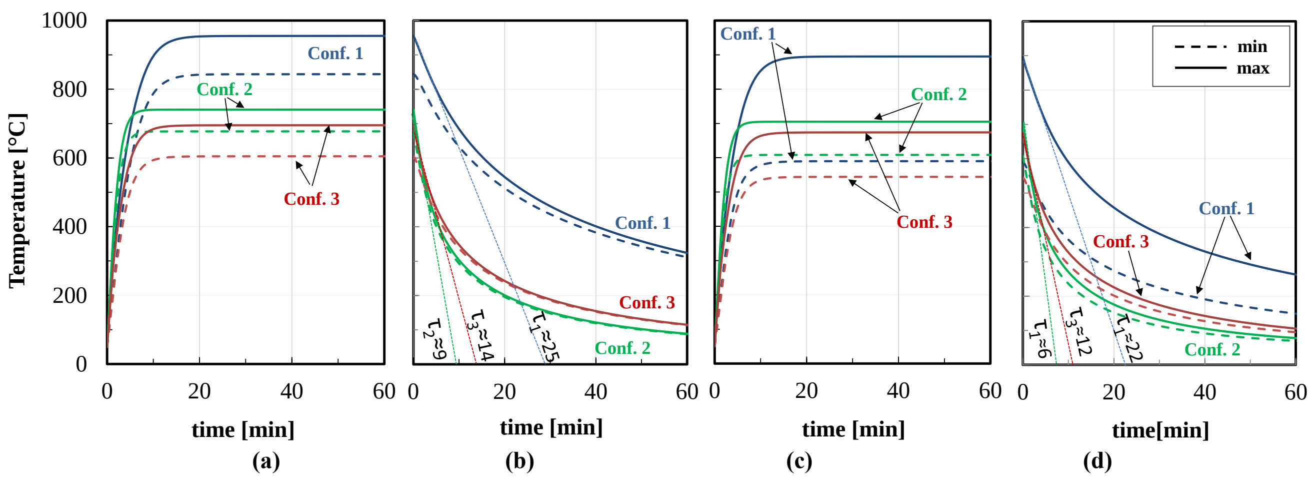

Fig. 4. Temperature evolution of the stacks in different configurations: (a) heating up internal zone, (b) cooling down internal zone, (c) heating up external zone, (d) cooling down external zone

Table 1
Assessment of pump configurations. The ranking goes in three steps from - (characteristic is not fulfilled) to + (characteristic is well fulfilled)

Characteristic	Configuration 1	Configuration 2	Configuration 3
Compactness	+	0	-
Effective pumping speed per unit mass of NEG	-	+	0
Gas load uniformity	-	+	0
Scalability	-	0	+
Modularity	-	0	+
Maintainability	-	0	+
Heater system reliability	0	-	+
Heating system: simplicity	0	-	0
Regeneration temperature uniformity	-	+	0
Heating efficiency	0	+	-
Characteristic time for cooling down	-	+	0

3.4. Discussion of results

Configurations 1 and 2 have very different characteristics; the configuration 1 has high thermal energy efficiency and it is very compact, whereas the configuration 2 maximizes the pumping speed and it allows to have fast thermal transient and obtain a good uniformity of temperature and gas load. Configuration 3 is halfway between the pros and cons of the other two configurations. Considering the above results the configuration 1 has a tight geometry, in which the disks influence each other; the configuration 2 has a loose geometry and the disk stacks act independently; the preferred geometry is configuration 3 which has a good compromise between engineering requirements and performance (Table 1).

4. Conceptual design description

The mock-up pump is composed by 9108 disks divided in 204 stacks with an overall size of 390x300x980 mm, with a total mass of getter of about 32 kg. It will possibly be the single NEG pump of largest scale constructed up to date. This solution shows a good uniformity among different 6-stack modules and non-uniformities are limited within the module itself, from the outer to the inner side of one disk. Each module is provided of four heaters for redundancy, connected two by two in series. The cartridges have a plug-in system for the installation on the support frame, in order to be compatible with remote handling. The modules are enclosed by an external cage, which gives rigidity to the structure, reduces the radiative heat exchange out of the getter material and limits the pumping speed, with a transmission probability close to the geometrical transparency.

The latter two effects were quantitatively studied (Fig. 5). The normalized effective pumping speed of one hexagonal module indicates that a transparency of 50% for the hexagonal cage is sufficient to reach 90% of the maximum pumping speed; at the same time, a transparency of 50% reduces the heat loss by about 50% (also increasing the temperature uniformity of the getter disks).

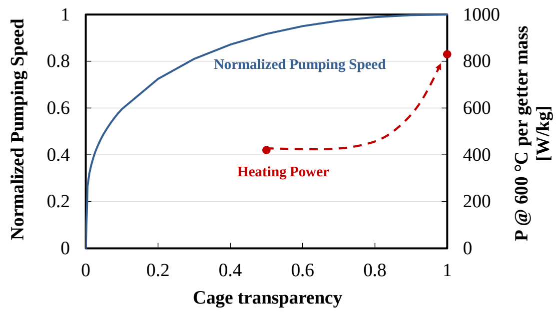

Fig. 5. Reduction of pumping speed *S* of a hexagonal module with external cage: normalized *S* as function of open area and heating power required to reach a steady-state condition of 600°C

5. Conclusion and outlooks

The conceptual design phase of the pump mock-up has been completed with the decision to proceed with the configuration 3. The next steps will be the finalization of the design in order to build the pump, and then start with the experimental campaign in the TIMO facility.

Acknowledgments

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References

[1] L.R.Grisham, P.Agostinetti et.al., vol. 87, Fusion Engineering and Design, 2012, pp. 1805-1815.

[2] G.Duesing, vol. 37, Vacuum, 1987, pp. 309-315.

[3] C.Day et.al, vol. 83, Vacuum, 2008, pp. 773-778.

[4] G. L. Saksaganskii, *Getter and Getter-Ion Vacuum Pumps*, 1994, pp. 254-301.

[5] K. Jousten, *Handbook of Vacuum Technology*, 2016, pp. 478-481.

[6] P.Sonato, P.Agostinetti et.al, vol. 57, Nuclear Fusion, 2017.

[7] E.Sartori and P.Veltri, vol. 90, Vacuum, 2013, pp. 80-88.

[8] E.Sartori, G.Serianni and S. Dal Bello, vol. 122, Vacuum, 2015, pp. 275-285.

[9] H.Haas, C.Day, A.Mack, S.Methe et.al., vol. 3, Yokohama,Japan: Proceedings of the 17th IAEA Fusion Energy Conference, 1998, pp. 1077-1080.