EUROfusion

EUROFUSION WPBB-PR(16) 14545

L. Frances et al.

Development and modelling of a multi-nozzle Vacuum Sieve Tray extraction facility

Preprint of Paper to be submitted for publication in
Tritium 2016 - 11t International Conference on Tritium Science and Technology

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Development and Modelling of a Multi-nozzle Vacuum Sieve Tray Extraction Facility

L. Frances [a], D. Demange [a], S. Konishi [b], M. Mertens [c], A. Muñoz [a], F. Okino [b]*

[a] Karlsruhe Institute of Technology, Institute for Technical Physics, Tritium Laboratory Karlsruhe,
Herrmann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany.

[b] Kyoto University, Institute of Advanced Energy, Kyoto, Japan.

[c] Ghent University, Department of Materials Sciences and Engineering, Center for Molecular Modeling, Ghent, Belgium.

* Corresponding author: laetitia.frances@kit.edu

KEYWORDS

Fusion, Breeding Blanket, DEMO, Tritium Extraction System

ABSTRACT

Advanced and very efficient technologies are likely required to ensure a proper tritium management in the perspective of DEMO and of the fusion machines. The vacuum sieve tray method is a promising technique due to its relative simplicity, its compactness and the high expected extraction efficiency. Efficient deuterium extraction has already been demonstrated during single-nozzle experiments. Nevertheless the study of multi-nozzle trays is required to upscale this technology to DEMO breeding blankets, since the possible reabsorption of tritium extracted from one droplet by another one could spoil the extraction efficiency. We developed a multi-nozzle facility to carry out deuterium extraction. Comparing single-nozzle and multi-nozzle extraction, it will allow quantifying different contributions to disturbances, included in an empirical model developed for hexagonal geometries, easy to upscale.

I. INTRODUCTION

Tritium extraction from Pb-16Li liquid breeding blanket seems still very challenging, especially in view of DEMO; advanced and very efficient technologies are likely required to ensure a proper tritium management in the fusion machine [1]. Amongst several techniques, the vacuum sieve tray (VST) has been selected as a candidate process to perform tritium extraction from liquid breeding blankets, along the EUROfusion project [2]. A vacuum sieve tray experiment is based on the flow of Pb-16Li from an upper chamber (UC), where it is saturated with hydrogen isotopes, to a lower chamber (LC) maintained under dynamic vacuum, where Q_2 is extracted (Q designates H, D or T). These chambers are separated by a tray of submillimeter diameter nozzles which forces Pb-16Li to form an instable liquid jet that breaks up forming droplets. The Q atoms are transported from the core of the falling droplets towards their outer surface where they recombine to form Q_2 that leaves the liquid metal and is recovered using a pump train.

This technique has been disregarded for a long time [3], assuming that the transport of Q in the droplets was governed by diffusion, actually too slow to realize an efficient extraction unit. But new experimental results obtained with deuterium and single nozzle VST highlighted enhanced extraction likely due to the high frequency oscillations of the Pb-16Li droplets when falling [4,5]. Since VST is simple and compact, it is considered now as a very promising method for extracting tritium from Pb-16Li blankets.

Nevertheless the study of multi-nozzle flanges is required to upscale this technology to DEMO breeding blankets since the possible reabsorption of tritium extracted from one droplet by another one could spoil the extraction efficiency.

Recently TLK developed a very detailed model implemented in a simulation tool to calculate Pb-16Li flow rate and velocity as well as extraction efficiency. This model takes into account accurate calculations of all pressure drops along the VST, but neglects the possible impact of multi-nozzle disturbances on extraction efficiency. These shall be quantified by comparing the experimental results obtained during multi-nozzle extractions of deuterium with the above mentioned single nozzle predictions. This will be fulfilled thanks to the multi-nozzle experiments to be analyzed with an

empirical model including different contributions to the decrease of extraction efficiency due to reabsorption.

II. VST: STATE OF THE ART

Deuterium extraction relying on a single-nozzle set-up was performed [4,6,7]. Tritium production due to the neutron bombardment of lithium in the breeding blanket was replaced by the initial dissolution of deuterium. Significant amounts of deuterium were extracted along the fall of the droplets towards the LC. The oscillations of the falling droplets and their diameter, predicted by Plateau-Rayleigh theory, were confirmed [6,7]. Those oscillations are proposed to explain that the mass transport of Q in the droplets is dramatically enhanced by the mechanical refreshing of Pb-16Li at the interface liquid / vacuum [4].

The extraction efficiency is mathematically described by the equation 1, were η is the extraction efficiency or extraction ratio, $M_{(t)}$ is the amount of deuterium extracted at the time t, M_∞ is the amount of deuterium initially dissolved, D is the quasi dispersion coefficient, r is the droplet radius and t_{fall} the falling time of the droplets [8].

$$\eta = \frac{M_{(t)}}{M_\infty} = 1 - \frac{6}{\pi^2} \times \sum_{n=1}^{\infty} \frac{1}{n^2} \times \exp\left(\frac{-D \times n^2 \times \pi^2 \times t_{fall}}{r^2}\right) \qquad (1)$$

Based on experimental results [4], a quasi-dispersion coefficient was derived with a value of 3.4×10^{-7} m².s^{-1} which is two orders of magnitude higher than the diffusion coefficient of 2.0×10^{-9} m².s^{-1} measured for deuterium by Reiter et al. [9].

The falling time t_{fall} (equation 2) is calculated depending on the flow velocity v_0 at the exit of the nozzles and on the falling height h (height of the LC reduced by the height of Pb-16Li accumulating at the bottom during the experiment).

$$t_{fall} = \frac{-v_0 + \sqrt{v_0 + 2gh}}{g} \qquad (2)$$

III. DETAILED MODEL FOR PRESSURE DROPS

A model to calculate accurately the velocity v_0 (equation 2) was developed, considering a detailed understanding of the pressure losses along the extraction unit [10]. The core of the extraction

unit for both single and multi-nozzle experiments consists in an upper chamber (UC), connected to a lower chamber (LC) with a tube accommodated with a valve (Fig. 2). This tube ends in the LC and is connected to a single or multi-nozzle tray. Two major contributions to the total pressure losses have been identified during Pb-16Li flow: the contraction at the connection of tube to the nozzle(s) and the viscous losses in the nozzle(s) [10]. The generalized Bernoulli equation is applied between the upper surface of the Pb-16Li and the exit of the nozzles to calculate the mass or volumetric flow rate by iterations, including the pressure losses. The flow velocity is deduced from the mass flow rate.

Beyond the calculation of the flow velocity at the exit of a nozzle, the model developed allows following all the main parameters during a simulated experiment such as the extraction efficiency, the falling height and falling time, each contribution to the total pressure losses, etc. (all of them vary during an experiment because e.g. the hydrostatic pressure at the nozzle outlet is dropping and the falling height is reduced by the height of Pb-16Li that accumulates in the LC). The extraction efficiency, the flow rate (or the velocity at the exit of the nozzle) depend on the temperature, the geometry of the chambers and of the nozzles, the pressure of deuterium applied for its dissolution in lead-lithium, all entered as input. The equations implemented in the model were translated in a logical diagram (Fig. 1) listing the main “input” and “intermediate” parameters with their influence on the “output” parameters.

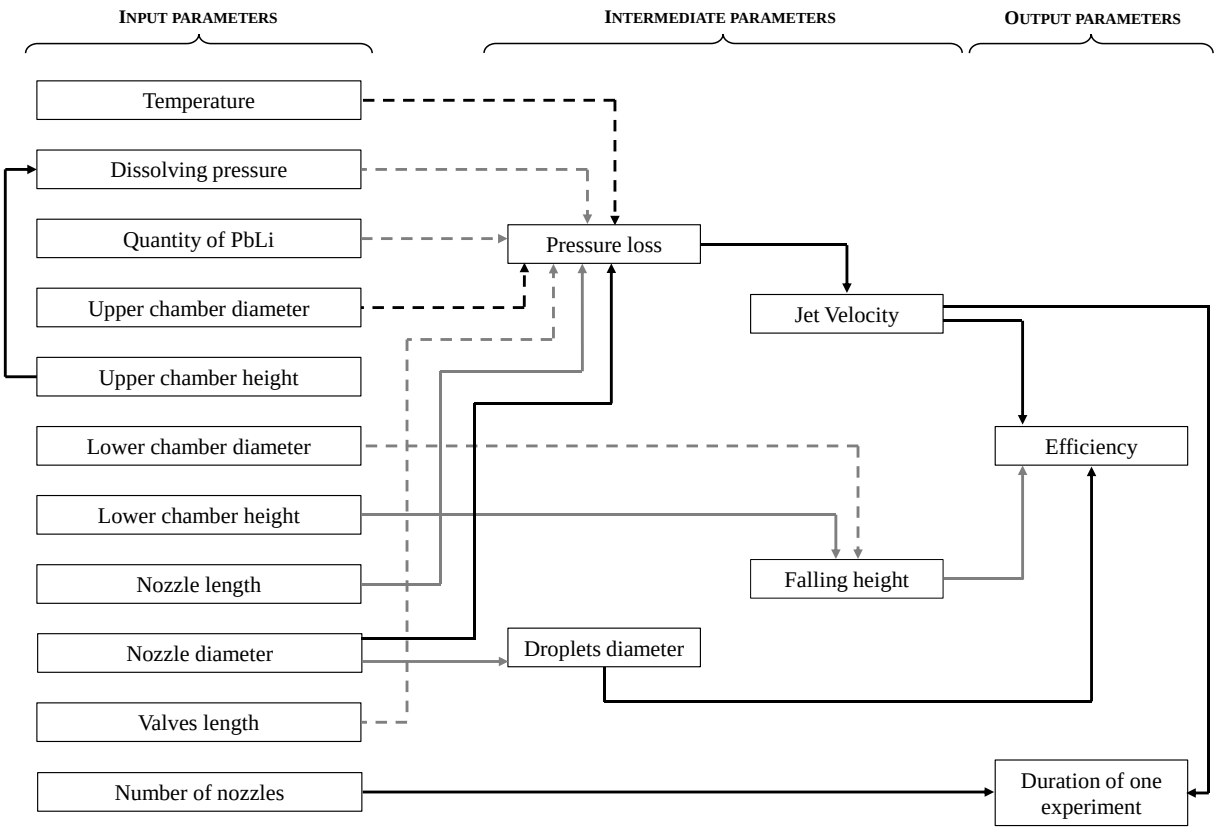


Fig. 1: Influence of the main input parameters on the main intermediate and output parameters. (The grey lines indicate that when one parameter increases the associated one also increases and reciprocally. The black lines link parameters evolving in opposite ways. The dashed lines indicate a minor influence while full lines indicate a major impact).

The immediate use of the model is the optimization of the design of the multi-nozzle extraction unit. The diameter and height of the both main chambers were decided considering for example the trade-off between extraction efficiency and experiment duration. The permeation was also taken into account, by designing a geometry favoring the dissolution and shortening the time it requires, to limit the amount of deuterium that permeates through the walls of the upper chamber during one experiment.

Nevertheless it should be highlighted that the limitation of the code is that it does not take into account yet any disturbance that can be due to multi-nozzle trays. In DEMO breeding blankets, the flow rates of lithium lead is expected to reach up to 30 000 $kg.s^{-1}$ [11] for the Dual Coolant Lithium Lead concept, when the order of magnitude of the mass flow rates per nozzle calculated so far is 10^{-2} $kg.s^{-1}$. The scale-up of VST to DEMO relevant flow rates requires multi-nozzle trays. Actually, when several

droplets are falling near from each other, Q_2 extracted from one droplet could be reabsorbed by another droplet falling in the surroundings, what could spoil the extraction efficiency.

IV. D_2 EXTRACTION WITH MULTI-NOZZLE VST

A facility was developed (Fig. 2) to quantify disturbances that can be encountered with multi-nozzle trays, by comparing simulated extraction efficiencies (neglecting any disturbance) to the experimental ones. The experiment will consist in flowing Pb-16Li from the UC towards the LC, through a tube implemented with a valve and ending in a VST tray. First deuterium will be introduced in the UC and put in contact with the molten alloy to be dissolved. Then, the valve separating the both chambers will be opened and the liquid metal will flow down from the UC to the LC through the tube and the tray of nozzles, located inside the LC. The deuterium extracted during the fall will be collected using one or several of the pumping ports available. The LC was actually designed with four CF63 flanges that enable an efficient and symmetric pumping, with a large conductance. The pumping ports can also easily be interchanged for observation windows. The commissioning of the experiment will include steps with two boron windows, to ensure a sufficient light and allow images capture relying on a high speed camera (400 frames per second). This way, the diameter of the droplets, their velocity as well as the frequency of their oscillations will be accessible. It is also the easiest way to check that there is no coalescence between the droplets falling close from each other.

The nature of the gas extracted will be checked by QMS (QMG 220 M1, PrismaPlus Compact mass spectrometer). The amount of gas extracted will be deduced from pressure and temperature measured in the calibrated collecting volume (150 ccm). The automatic valve between the UC and the LC (Swagelok SS-8BW-VCR-5CM) will automatically close before all the Pb-16Li flowed down, to avoid the deuterium in equilibrium with the liquid metal in the UC to enter the LC and the collecting volume. Between two successive experiments, the liquid Pb-16Li will be transferred back from the LC to the UC by helium pressurization. The design of the chambers and especially their height were also optimized and decided to allow the transfer of Pb-16Li by applying a gas pressure below 1.5 bar. Then the extraction unit is a non-pressurized equipment. The resulting dimensions of the UC and LC are summarized in Table 1.

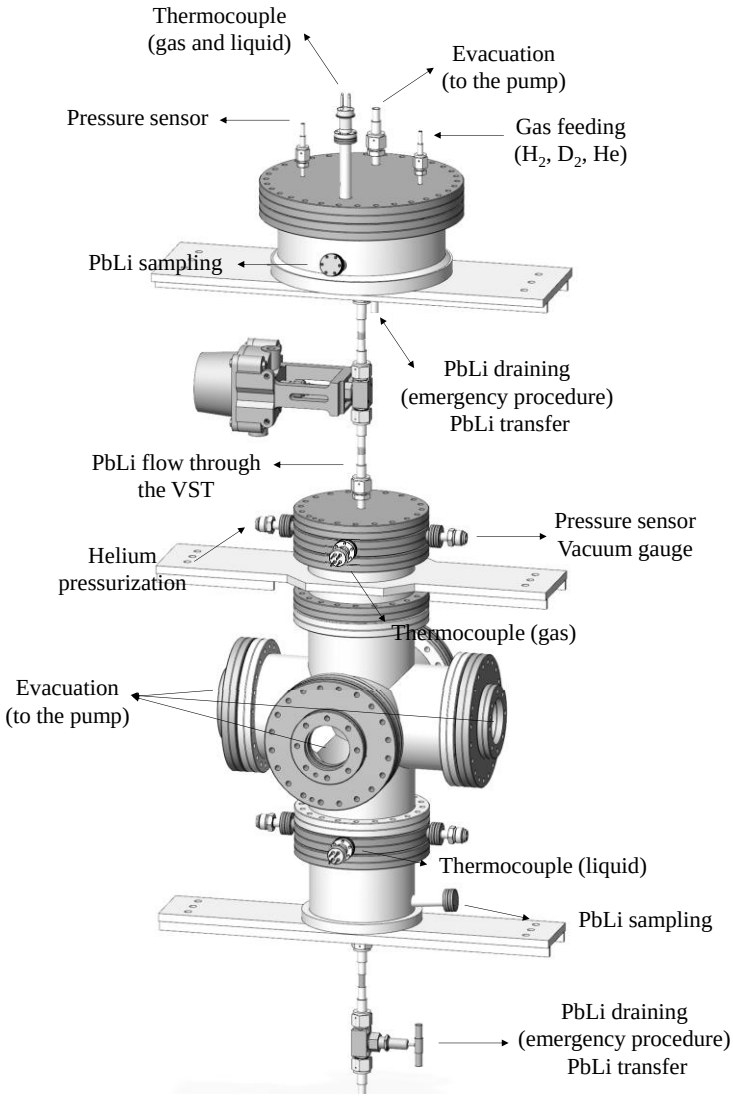


Fig. 2: 3D view of the optimized core of the multi-nozzle extraction unit: the Upper Chamber (UC), the Lower Chamber (LC) with the functions of the different feedthrough and connections.

Tab. 1: Dimensions of the optimized lower chamber and upper chamber

	Upper chamber	Lower chamber
Inner radius (mm)	121	76.5
Height (mm)	82	610

The optimization of the UC resulted in an inner radius of 121 mm and a height of 82 mm. Those dimensions favor the kinetics of dissolution of deuterium in the Pb-16Li. Then the permeation will be limited during this step. Several feedthrough will be implemented to allow measuring the temperature and pressure of the gas phase, but also to measure the temperature of the liquid alloy. Some additional feedthrough will be dedicated to the gas feeding or evacuation of the chamber and of Pb-16Li flow down and transfer.

The optimized Lower Chamber will be 610 mm high, with an inner radius of 76.5 mm. The height has been especially optimized to result in high extraction efficiencies that should favor the multi-nozzle disturbances, while keeping the total height of the set-up relatively low. This way, the helium pressure to apply for Pb-16Li transfer is limited to 1.5 bar.

For the both chambers, a CF 16 connector at the bottom part has been added to sample Pb-16Li before and after extraction. The bottom of the UC and of the LC will also be manufactured with an inclination of 3 °C to avoid Pb-16Li sticking.

The facility was designed to operate with 10 kg of eutectic Pb-16Li provided by Stachov (massic percentage of lead of 99.22 %). Deuterium extraction will be performed at different temperatures, ranging from 350 up to 450 °C and applying different dissolution pressures ranging from 30 up to 150 mbar. Different multi-nozzle trays that were also optimized relying on the single nozzle simulation code [10] will be alternatively connected and studied. The code was used to select the most relevant nozzle diameter, targeting experiments longer than 1 minute, for trays including up to 19 nozzles and an extraction efficiency higher than 80 %, required for DEMO breeding blankets. A typical experiment was simulated with this resulting extraction unit and realistic operation conditions. It provides orders of magnitude for the velocity, the falling time, the flow rate and the extraction efficiency (Tab. 2).

Tab. 2: Calculated velocity at the exit of the nozzles, falling time, flow per nozzle, extraction efficiency, for a typical experiment relying on the optimized extraction unit.

Input parameters		Output parameters	
Dissolving pressure (mbar)	50	Velocity (exit of the nozzles) ($m.s^{-1}$)	2.56
Nozzle diameter (mm)	0.6	Falling time (s)	0.154
Nozzle length (mm)	2	Flow per nozzle ($kg.s^{-1}$)	7.2×10^{-3}
Temperature (°C)	400	Extraction efficiency (%)	88.5
		Experiment duration (1 nozzle) (min)	24

V. MULTI-NOZZLE MODELLING

A hexagonal geometry has been retained as it presents many advantages:

- it can be defined using one single geometrical parameter (the gap *g*, which is the distance between two adjacent nozzles) what simplifies the study,
- a hexagonal geometry offers one center of symmetry and six symmetry axis, resulting in equivalent nozzles regarding their location on the tray,
- the dimensions of the tray can be easily scaled up or adjusted as the number of nozzles *N* and the number of concentric hexagons *n* composing the flange are mathematically related (equation 3).

$$N = 3n^2 + 3n + 1 \qquad (3)$$

The disturbances will be quantified and analyzed relying on a two dimensional empirical model. The latter includes six different dimensionless disturbances p_{XY}. X indicates the distance at which the droplets inducing and undergoing the disturbance are generated from each other. α is the adopted notation for a distance of one gap, β for a distance of √3 times the gap. Y indicates how many droplets are generated in the close surroundings (at a distance of one gap) of the droplets leading to the disturbance. Two examples are given on the Figure 3, with the disturbances named $p_{\alpha 6}$ and $p_{\beta 4}$. On this sketch, *t* designates the nozzles generating the droplets disturbed while *d* designates the nozzles

generating the droplets inducing the perturbation. *s* indicates which nozzles are considered to impact the perturbation created by *d*.

A recurrence law has been evidenced between the number of occurrences for each disturbance, the number of nozzles *N* and the number of concentric hexagons *n* composing the flange (equation 4). The strategy of the study will consist in measuring the extraction efficiency η, to be compared with the simulated extraction efficiency η_i (neglecting the multi-nozzle disturbances), to calculate the six identified disturbances $p_{\alpha 3}$, $p_{\alpha 4}$, $p_{\alpha 6}$, $p_{\beta 3}$, $p_{\beta 4}$, $p_{\beta 6}$.

$$\eta = \eta_i - \frac{1}{N}\left[18p_{\alpha 3} + (24n - 24)p_{\alpha 4} + (18n^2 - 18n + 6)p_{\alpha 6} + 12p_{\beta 3} + (18n - 18)p_{\beta 4} + (18n^2 - 24 + 6)p_{\beta 6}\right] \quad (4)$$

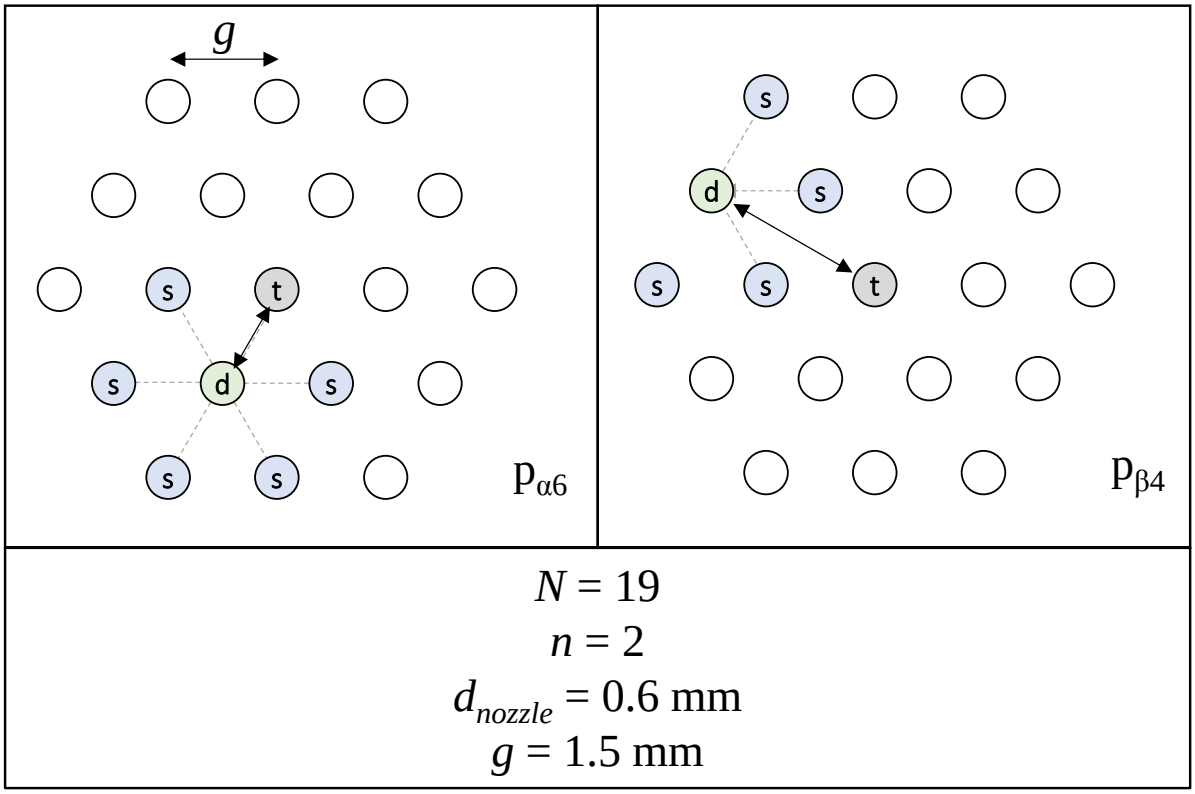
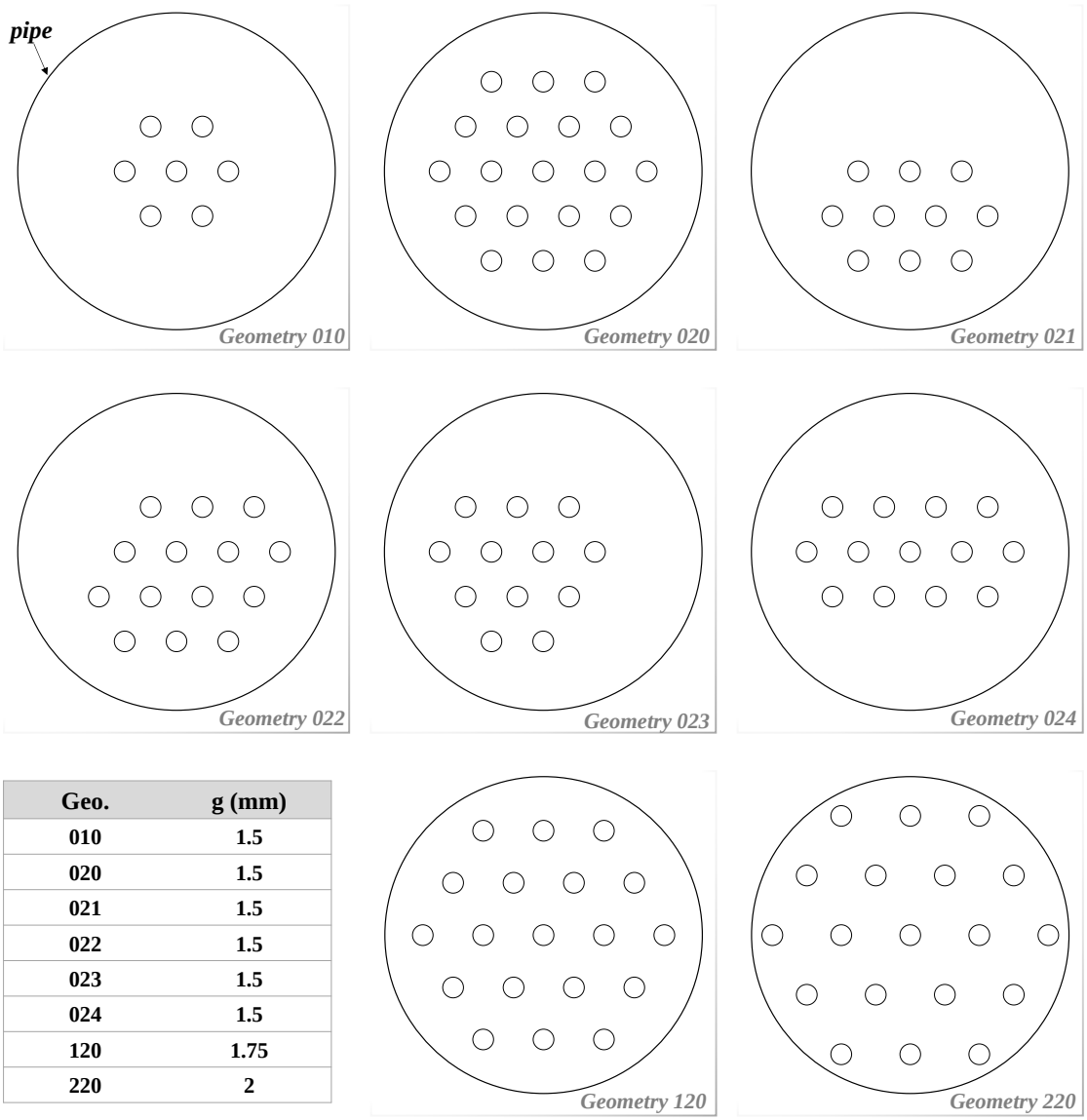


Fig. 3: Scaled up top view of a 19 nozzles flange with two examples of disturbances $p_{\alpha 6}$ and $p_{\beta 3}$. *g* is the gap between two adjacent nozzles, *t* the nozzles generating the droplets disturbed, *d* the nozzles generating the droplets inducing the perturbation, which can themselves be affected by the droplets flowing from the nozzles *s*.

Six different configurations are required and were developed to study the disturbances p_{XY} (Fig. 4) as the equation 4 lets appear six unknown values to define. As it is expected to play a major role on the multi-nozzle perturbation, the gap *g* will also be qualitatively studied during the first experimental campaign. Three different values of 1.5, 1.75 and 2 mm have been chosen considering the inner diameter of the pipes and the minimum gap estimated to avoid coalescence.



Geo.	g (mm)
010	1.5
020	1.5
021	1.5
022	1.5
023	1.5
024	1.5
120	1.75
220	2

Fig. 4: Scaled up top view of the eight flanges to be tested to determine the six contributions to possible multi-nozzle perturbations included in the empirical model and to study the impact of the gap *g* on the extraction efficiency inflection.

VI. CONCLUSIONS

The scale up of vacuum sieve trays, which is a promising technique to extract tritium from Pb-16Li breeding blankets, requires a deep understanding of multi-nozzle trays behavior. We first developed a model describing single nozzle experiments including precise calculation of the pressure losses. It neglects the possible reabsorption of Q_2 extracted from one droplet by another falling in its surroundings, but provides a complete follow-up of the flow rate, the velocity, the duration of the experiment and the extraction efficiency. We relied on those simulated results to develop an optimized multi-nozzle facility. The experimental results will be analyzed with an empirical model presented and discussed. It relies on the use of eight different multi-nozzle trays.

The multi-nozzle extraction experiment is considered to be a preliminary experiment but also complementary to tritium extraction experiments. Actually, technical issues such as corrosion, permeation, Pb-16Li solidification, will be then tackled along deuterium extraction before handling tritium. As a consequence, beyond the understanding of multi-nozzle behaviors, the multi-nozzle vacuum sieve tray will be also a crucial experiment to develop the next setup to be operated with tritium.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[1] D. Demange, R. Antunes, O. Borisevich, L. Frances, D. Rapisarda, A. Santucci, et al., Tritium extraction technologies and DEMO requirements, Fusion Eng. Des. (n.d.). doi:10.1016/j.fusengdes.2016.01.053.
[2] L.V. Boccaccini, G. Aiello, J. Aubert, C. Bachmann, T. Barrett, A. Del Nevo, et al., Objectives and status of EUROfusion DEMO blanket studies, Fusion Eng. Des. (n.d.). doi:10.1016/j.fusengdes.2015.12.054.
[3] H. Moriyama, S. Tanaka, D.. Sze, J. Reimann, A. Terlain, Tritium recovery from liquid metals, Fusion Eng. Des. 28 (1995) 226–239. doi:10.1016/0920-3796(95)90043-8.

[4] F. Okino, K. Noborio, R. Kasada, S. Konishi, Enhanced Mass Transfer of Deuterium Extracted from Falling Liquid Pb-17Li Droplets, Fusion Sci. Technol. 64 (2013) 543–548.
[5] F. Okino, P. Calderoni, R. Kasada, S. Konishi, Feasibility analysis of vacuum sieve tray for tritium extraction in the HCLL test blanket system, Fusion Eng. Des. (2015). doi:10.1016/j.fusengdes.2015.10.004.
[6] Y. Yamamoto, M. Ichinose, F. Okino, K. Noborio, S. Konishi, Design of tritium collecting system from LiPb and LiPb dropping experiment, Fusion Sci. Technol. 60 (2011) 558–562.
[7] F. Okino, K. Noborio, Y. Yamamoto, S. Konishi, Vacuum sieve tray for tritium extraction from liquid Pb–17Li, Fusion Eng. Des. 87 (2012) 1014–1018. doi:10.1016/j.fusengdes.2012.02.071.
[8] J. Crank, The mathematics of diffusion, Clarendon Press, Oxford [Eng], 1975.
[9] F. Reiter, Solubility and diffusivity of hydrogen isotopes in liquid Pb-17Li, Fusion Eng. Des. 14 (1991) 207–211. doi:10.1016/0920-3796(91)90003-9.
[10] M. Mertens, D. Demange, L. Frances, Model and simulation of a Vacuum Sieve Tray for T extraction from liquid PbLi breeding blankets, Submitted to Fusion Eng. Des. (n.d.).
[11] S. Smolentsev, N.B. Morley, M.A. Abdou, S. Malang, Dual-coolant lead–lithium (DCLL) blanket status and R&D needs, Fusion Eng. Des. 100 (2015) 44–54. doi:10.1016/j.fusengdes.2014.12.031.