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Commissioning of Multi-Nozzle Vacuum Sieve Tray at the Tritium Laboratory Karlsruhe

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Performance evaluation of the Multi-Nozzle Vacuum Sieve Tray facility at the Tritium Laboratory Karlsruhe

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Tritium will be produced in breeding blankets by neutron bombardment of lithium to ensure the self-sufficiency of fusion power plants. Then, the tritium must be extracted for further fueling of the plasma. The Vacuum Sieve Tray (VST) technique has been proposed for the tritium extraction system of liquid blankets in the European DEMO. Its principle of operation consists in extracting the tritium dissolved in oscillating Pb-16Li droplets falling inside a vacuum chamber. The Multi-Nozzle VST (MNVST) setup was erected at the Tritium Laboratory Karlsruhe (TLK) to study the scalability of the VST technique, as well as to serve as a preliminary deuterium/lead-lithium facility before construction of a new rig to be operated with tritium. Preliminary tests and numerical simulations were performed to define the experimental plan based on the distinguishability of the amount of deuterium that would be collected during the different experiments. As a result, six equilibrium pressures (10, 50, 100, 200, 300, 400 mbar), three Pb-16Li temperatures (350, 400, 450 °C) and two nozzle geometries (1 and 19 nozzles) will be tested during the MNVST experiments.

Keywords: tritium extraction, tritium recovery, liquid breeding blanket, lithium-lead, vacuum sieve tray

1. Introduction

A fusion power plant of 1000 MWe is expected to consume 167.4 kg of tritium per year, whereas currently only about 27 kg are available from the Canadian CANDU reactors after 40 years of operation [1]. Therefore, demonstrating tritium self-sufficiency is one of the main goals of DEMO [2]. Tritium will be produced in breeding blankets by neutron bombardment of lithium. Within the lithium-lead loop, an efficient tritium extraction system is needed to recover the produced tritium to fuel the plasma. For the liquid breeder concepts, Gas Liquid Contactors (GLC) are planned for the European TBM module in ITER [3]. However, the maximum extraction efficiency that this technology has demonstrated is 30% [4]. Therefore, other two technologies, with promising extraction efficiencies but that still need to be experimentally demonstrated, are under study in the perspectives of the EU-DEMO: the Permeator Against Vacuum (PAV) and the Vacuum Sieve Tray (VST) [5].

The Vacuum Sieve Tray (VST) technology consists in allowing the liquid metal to fall through submillimeter-diameter nozzles in a chamber kept under vacuum. The lithium-lead initially falls in form of liquid jets, which eventually break into droplets. While the droplets are falling, the tritium dissolved in atomic form is transported towards their surface. At the liquid/vacuum interface, recombination occurs and T_2 is extracted with a pumping system.

At the Tritium Laboratory Karlsruhe (TLK), a deuterium VST experimental setup was assembled: the Multi-Nozzle Vacuum Sieve Tray (MNVST). This setup was designed to study the effect of the experimental variables (e.g. Pb-16Li temperature, droplet falling time) on the amount of deuterium extracted and the scalability of the VST technique. This facility is aimed at performing experiments with deuterium/lead-lithium prior to the construction of the tritium setup.

Numerical simulations to estimate the expected amounts of deuterium collected have been performed. In this analysis, the accuracies of the measuring devices were included to determine the uncertainties expected along the experiments. These results are of major importance to define an experimental plan that allows measuring the impact of the experimental variables (e.g., Pb-16Li temperature).

2. The Multi-Nozzle Vacuum Sieve Tray facility (MNVST)

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Fig. 2. Gas collection of the MNVST facility

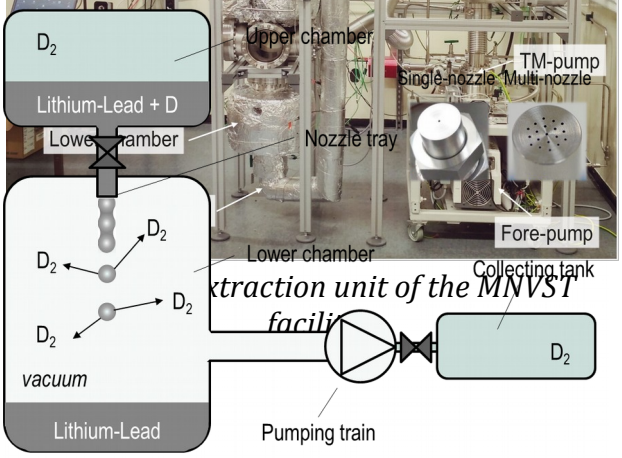

Fig. 3. Scheme of the MNVST experiment

MNVST is a flexible setup, which is operated with deuterium. It features replaceable nozzle trays (single-nozzle vs multi-nozzle geometries) and two windows to record the hydrodynamics of the falling lithium-lead with a high-speed camera. Error: Reference source not found and Error: Reference source not found show the assembly of the MNVST facility. The Pb-16Li circuit is fully covered with ceramic fiber (except the windows in the lower chamber) to ensure the required thermal insulation and maintain the temperature of the liquid lithium-lead (350 °C - 450 °C).

Error: Reference source not found presents a scheme of the MNVST facility. A typical run starts with the dissolution of deuterium into the lithium-lead in the upper chamber. This process is done in static conditions while monitoring the D_2 pressure. The dissolution in Pb-16Li is considered to be finished when the decrease in pressure is only due to permeation through the walls of the chamber. The gas pressure at the end of the dissolution phase is defined as the equilibrium pressure. At that moment, the extraction phase starts and the lithium-lead falls into the lower chamber through the nozzle tray (examples shown in Error: Reference source not found). The deuterium extracted in the lower chamber is collected in the collecting tank with the pumping train. A quadrupole mass spectrometer is attached to the collecting tank to measure the composition of the gas (only D_2 expected). At the end of the experiment, the lithium-lead is transferred back to the upper chamber through the transfer line (see Error: Reference source not found) by argon pressurization in the lower chamber.

3. MNVST experimental strategy

During the MNVST experimental campaign, the amount of deuterium collected will be determined with the *p-V-T* method, considering ideal gas law. The impact of the following parameters on the amount of collected gas will be investigated: the equilibrium pressure in the upper chamber, the Pb-16Li temperature, the number of nozzles and the vacuum level in the lower chamber.

3.1. Equilibrium pressure in the upper chamber

The D_2 pressure in the upper chamber at the instant before the extraction experiment starts (i.e. equilibrium pressure) impacts the amount of deuterium dissolved in the lithium-lead and the speed of the falling liquid metal. The equilibrium pressure has to be between 10 – 1000 mbar in order to obtain reliable measurements and remain below the maximum pressure allowed in the facility (1500 mbar).

3.2. Pb-16Li temperature

The temperature of the lithium-lead affects the amount of deuterium dissolved, the volume of the lithium-lead and its viscosity (and thus the speed of the falling liquid metal). The Pb-16Li operation temperature has to be between 350 – 450°C to ensure complete melting (melting point: 235°C) and remain below the maximum temperature allowed in the facility (500°C).

3.3. Number of nozzles

The number of nozzles influences the flow and the speed of the falling liquid. Due to friction losses in the nozzles, the greater the number of nozzles, the slower the Pb-16Li will fall in the lower chamber. In the MNVST facility, the first experimental campaign will be performed with one nozzle. This will allow to benchmark the Pb-16Li hydrodynamic code presented in [6], which was adapted to the MNVST facility. Then, a multi-nozzle campaign is set to study the scaling-up of the system and to investigate potential re-absorption of the D_2 by other Pb-16Li droplets. The maximum number of nozzles that the current setup allows is 19, which is limited by the tray diameter and the minimum pitch (distance between nozzles).

3.4. Level of vacuum in the lower chamber

From results obtained by Okino et al. [7], the mass transport coefficient of deuterium inside the Pb-16Li droplet (3.4×10^{-7} m^2 s^{-1}, at 400°C) is much greater that the diffusion coefficient given by Reiter (1.2×10^{-9} m^2 s^{-1}, calculated for 400°C) [8] or Edao et al. (5.0×10^{-9} m^2 s^{-1}, calculated for 400°C) [9]. Therefore, in principle, the deuterium partial pressure in the lower chamber should not affect the gas extracted, since the transport in the droplets is not governed by diffusion. However, for very low D_2 partial pressure (high vacuum) or high concentrations of D in the lithium-lead, a different regime may exist, in which the limiting process is no longer the transport of deuterium inside the droplets but the recombination at the liquid-vacuum interface. Therefore, the influence of the level of vacuum in the lower chamber on the amount of extracted gas will be also tested. The

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minimum pressure to be tested is 1×10^{-5} mbar to remain above the vapour pressure of lithium-lead (2.7×10^{-6} mbar, calculated for 450 °C [10]).

4. Uncertainty of the amount of D_2 collected

The amount of deuterium collected will be determined with the volume of the collecting tank, the gas pressure and temperature. Thus, the uncertainty of the moles of collected gas depends on the uncertainty of the tank volume, and the accuracy of the measuring sensors (pressure and temperature).

The volume of the collecting tank was measured with the method presented in [11] and determined to be 151.78 ± 0.53 ml. The pressure sensor in the collecting tank, model PTA227 (EFE), with 1000 mbar full scale, has a reported uncertainty of ±0.75 mbar. The K-type thermocouple installed inside the collecting tank has an uncertainty of ±1.2°C.

The calculations of the uncertainties for the number of moles of the gas collected were done by following the recommendations for uncorrelated quantities given in [12].

5. Estimation of D_2 collected during experiments

The impact of the different variables (equilibrium pressure, Pb-16Li temperature and number of nozzles) on the amount of deuterium collected was simulated to determine the uncertainty of the measurements. These results will be taken as input to define the operational conditions of the experimental campaign.

Due to the disagreement of Sieverts' constant in the literature [13], the estimation of the amount of deuterium dissolved suffers from a discrepancy of several orders of magnitude. The intermediate value reported by Edao et al. (1.1×10^{-2} mol m^{-3} $Pa^{-1/2}$, calculated for the range 350 – 450°C) [9] was used for the calculations presented in this paper.

The numerical code presented in [6] was adapted to the MNVST experiment and was used to simulate the expected extraction efficiency shown in Fig. 1, Fig. 2 and Fig. 3, using the mass-transport coefficient reported by Okino et al. (3.4×10^{-7} m^2 s^{-1}) [7]. The determination of the amount of deuterium collected, shown in Fig. 1, Fig. 2 and Fig. 3, assumes an estimated collection efficiency of 35% (i.e. the ratio between the amount of deuterium expected in the collecting tank and the amount of deuterium released in the lower chamber) and10 kg of Pb-16Li. The error bars of Fig. 1, Fig. 2 and Fig. 3 were calculated with the uncertainties given in Section 4 (pressure, temperature and volume of the collecting tank), simulating the measurement of the gas in the collecting tank.

5.1. Impact of the equilibrium pressure in the upper chamber

Fig. 1 shows the expected impact of the equilibrium pressure in the upper chamber on the amount of collected deuterium for experiments that would be performed with a single nozzle. The calculated uncertainties are lower than 7.5%. The maximum uncertainty is obtained at the lowest pressure measured in the collecting tank: 9.98 ± 0.75 mbar. Comparative measurements of 50 mbar difference are distinguishable. Therefore, the first experimental campaign (with single nozzle) will investigate the six equilibrium pressures presented in Fig. 1: 10, 50, 100, 200, 300, 400 mbar.

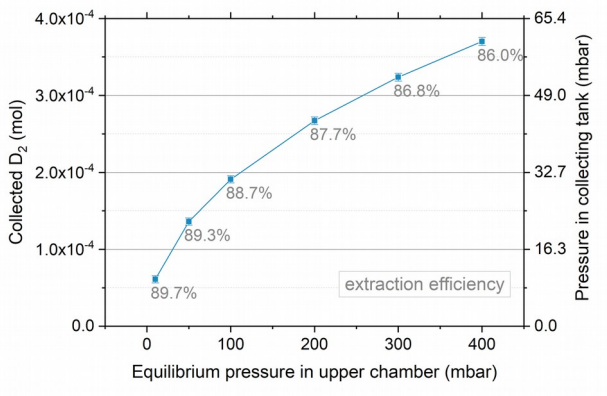

Fig. 1. Estimation of deuterium collected for experiments with a single nozzle and Pb-16Li temperature of 400 °C as a function of the equilibrium pressure in the upper chamber.

5.2. Impact of the Pb-16Li temperature

Fig. 2 shows the expected impact of the Pb-16Li temperature on the amount of collected deuterium for experiments that would be performed with a single nozzle. The calculated uncertainties are lower than 1.4%. Measurements of 50°C difference could be distinguishable, allowing for three runs within the range 350 – 450°C. Therefore, the first experimental campaign (with single nozzle) will investigate the three Pb-16Li temperatures presented in Fig. 2: 350, 400, 450 °C.

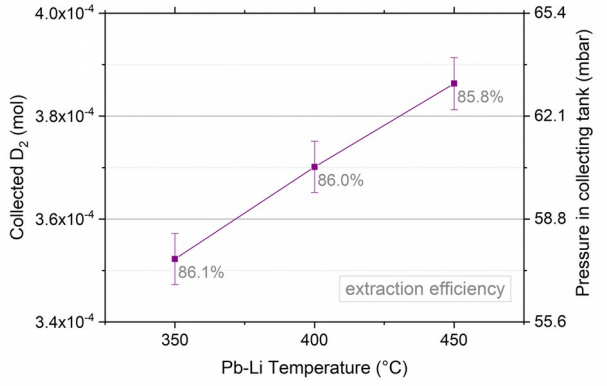

Fig. 2. Estimation of deuterium collected for experiments with a single nozzle and equilibrium pressure in the upper chamber of 400 mbar as a function of the Pb-16Li temperature.

5.3. Impact of the number of nozzles

Fig. 3 shows the expected impact of the number of nozzles on the amount of collected deuterium. The results presented neglect any possible re-absorption of D_2 by other Pb-16Li droplets (this effect will be investigated

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during the multi-nozzle experimental campaign). The uncertainties in Fig. 3 are shown to be lower than 1.4%. The effect of the number of nozzles within the given range is very low: only 19 nozzles seem to be distinguishable from one nozzle. Therefore, the first multi-nozzle sieve tray to be tested will be the one of 19 nozzles. If any re-absorption effect is identified (i.e. measured amount of collected deuterium much lower than the initially expected in comparison with the single nozzle), other multi-nozzle geometries with lower number of nozzles would be tested as well. Otherwise, a larger number of nozzles should be considered and tested.

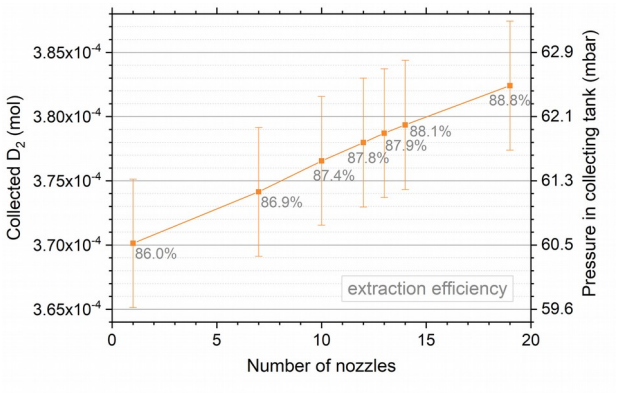

Fig. 3. Estimation of deuterium collected for experiments with equilibrium pressure in the upper chamber of 400 mbar and Pb-16Li temperature of 400 °C as a function of the number of nozzles.

5. Conclusions

During the first experimental campaign of MNVST, comparative experiments will be performed to investigate the effect of the equilibrium pressure in the upper chamber, Pb-16Li temperature, number of nozzles and level of vacuum in the lower chamber on the amount of collected deuterium. Numerical simulations were performed to predict the amount of gas collected as a function of the equilibrium pressure in the upper chamber, Pb-16Li temperature and number of nozzles. The uncertainties of the amount of gas collected were calculated using the corresponding errors associated with the temperature and pressure measurements (±1.2 °C and ±0.75 mbar, respectively) and collecting tank volume (151.78±0.53 ml). For the simulated scenarios, it was found that the uncertainties do not exceed 7.5% for small amounts of collected gas (6.1×10^{-5} mol), and they are lower than 1.4% for amounts of collected deuterium above 3.5×10^{-4} mol. These results show that the amounts of collected deuterium obtained from experiments with a single nozzle, six different equilibrium pressures (10, 50, 100, 200, 300 and 400 mbar) and three Pb-16Li temperatures (350, 400, 450 °C) are measurable. Therefore, these experimental conditions are selected for the first MNVST campaign (with single nozzle). The results reported here, which neglect re-absorption effects, also show that only the 19-nozzle geometry should produce distinguishable results in comparison with the single nozzle. The study of the possible re-absorption effects will be investigated in a later stage.

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