EUROFUSION WPBB-CP(16) 16487

M Kordac et al.

Helium Bubble Release from Pb-16Li within the Breeding Blanket

Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

Helium bubble release from Pb-16Li within the Breeding Blanket

Michal Kordač, Lukáš Košek

Research Centre Rez, Husinec - Řež, Czech Republic

To assess the extent of the helium gas release, a simplified model of a single sector of the European DEMO breeding blanket had been developed and local helium production rates have been calculated. Based on recent development of the blanket geometry, it is possible to estimate the local gas bubble release rate within each module, the gas bubble release profiles along the Pb-16Li conduits and the gas composition.

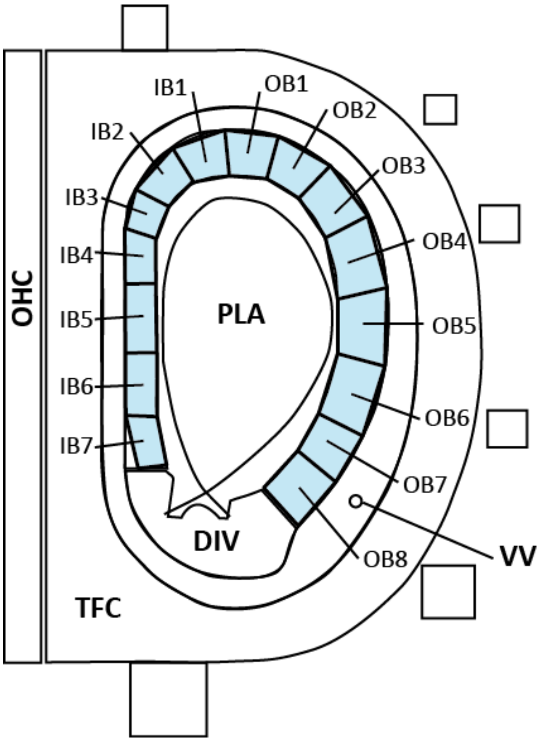

Fig. 1 Basic components of DEMO tokamak

Keywords: Pb-16Li, Breeding blanket, Helium bubbles, DEMO

1. Introduction

In the prospect of future power plants based on fusion of deuterium and tritium in a plasma, the fuel self-sufficiency is a major requirement [1]. Only very small amounts of tritium occur naturally because of cosmic rays interaction with atmosphere. Thus, the tritium will be produced on-site in the future fusion power plant using the neutron capture reaction in ^{6}Li, i.e.

$${}^{6}_{3}Li+{}^{1}_{0}n \rightarrow {}^{4}_{2}He+{}^{3}_{1}T+4.7\,MeV \quad .$$

To achieve sufficient production, various concepts of breeding blankets are studied in the framework of the EUROfusion project. These blankets are based either on using Li-containing ceramics, e.g. HCPB (Helium-cooled Pebble Beds), or liquid Pb-16Li alloy, e.g. HCLL (Helium-cooled Lithium Lead), WCLL (Water-cooled Lithium Lead), DCLL (Dual Coolant Lithium Lead) , for tritium breeding [2].

As mentioned above, helium is a by-product of the tritium breeding reaction. The LIBRETTO experiments [3,4] revealed that bubble formation may occur within the Pb-16Li alloy as a result of very low gas solubility in liquid Pb-16Li. Successively, concerns were raised [5] about the viability of the breeding blanket concepts based on liquid Pb-16Li, especially in case of the DCLL concept.

author's email: Michal.Kordac@cvrez.cz

2. Helium migration analysis

Principal geometry of the DEMO reactor system used in the present study was defined based on system code studies [6]. The geometry definition shown in Error: Reference source not found includes vertical and radial dimensions of the main components like central solenoid (OHC), toroidal field coils (TFC), vacuum vessel (VV), breeding blanket (BLA), plasma (PLA) and divertor (DIV). The blanket is subdivided into segments in radial direction and into modules in poloidal direction. Typically, there are considered 7 inboard modules IB1-IB7 and 8 outboard modules OB1-OB8 connected in parallel to the Pb-16Li distribution piping. Around the doughnut-shaped tokamak, the geometry model considers 32 inboard segments and 48 outboard segments, which are joined in loops [7,8]. In each loop, Pb-16Li passes through a blanket segment, tritium extraction system, heat exchanger and coolant purification system before it is returned back into the blanket.

The material balance of gaseous species in the blanket system can be written as:

$$i, \in ¿ + V_{BM} r_i = \acute{n}_{PbLi} x_{i,out} + y_i \acute{n}_{gas}$$
$$\acute{n}_{PbLi} x_{¿}$$

The two terms on the right hand side provide the distribution of the gaseous species between the fraction dissolved in liquid and in bubbles. The ratio of the two is given by a gas-liquid equilibrium condition, which for Helium can be expressed using Henry's law:

$$x_{He,out} \leq S \cdot x_{He}^{¿} = S \cdot k_H P_{gas}$$

where *S* is the supersaturation ratio $\left(x_{He} / x_{He}^{¿} \right)$ of the Pb-16Li. For successful bubble nucleation, a certain threshold must be reached before a cluster of helium atoms evolves into a stable bubble. The threshold can be estimated through bubble nucleation theories. The classical nucleation theory predicts supersaturation values up to 16.7 [9] to reach significant number of bubbles produced through the homogeneous nucleation mechanism. This value is largely reduced for the case of heterogeneous nucleation, where surface wettability of the seeding particle plays a key role. Value of about 1.4 is predicted for typical wetting angle of stainless steel by lead alloys of 120° – 150° [10–12]. Once stable gas-liquid interface is established, either in a form of stable bubbles or in a form of a gas pocket, desorption will continue until the thermodynamic equilibrium is reached, i.e. until $S = 1$.

The gas pressure is given as a sum of the hydrostatic pressure of the Pb-16Li and the pressure of the cover gas:

$$P_{gas} = P_{cover\ gas} + h \rho_{pbLi} g$$

The contribution of the surface tension to the gas pressure inside the bubble is omitted. Such assumption is valid for bubbles of sufficient size (of the order of several mm) and is certainly applicable to larger gas pockets, in which the surface curvature is negligible.

The calculations were performed for mean temperature in the blanket of 400°C and total tritium production rate of 385 g/day. Material properties of Pb-16Li used in the calculation are given in Table 1.

Table 1 Material properties of Pb-16Li at 400°C

Molar weight of Pb-16Li	0.1732 kg mol^{-1}
Density	9720 kg m^{-3}
Surface tension	0.442 kg s^{-2}
Henry's constant k_H	$3 \cdot 10^{-14}$ mol$_{He}$ mol$_{PbLi}^{-1}$ Pa^{-1}
Molar weight of helium	0.004 kg mol^{-1}
Pressure of the cover gas	100 kPa

3. Results

3.1 General considerations

Material balance of the breeding blanket as a whole reveals that the calculation is very sensitive to the total pressure of the alloy and the Pb-16Li flow rate, which dissolves produced helium. Fig. 2 and Fig. 3 show the calculated helium gas formation rate. Curves are drawn for normal operating conditions of the breeding blanket.

Fig. 2 shows the effect of total pressure. The gas phase generation rate is increasing with decreasing Pb-16Li flow rate for all the values of the pressure. At lower flow rates (up to 1 000 kg/s), significant rate of gas phase generation occurs at all values of the pressure. The amount of gas might be limited only due to the bubble nucleation barrier mentioned above and in such case the solution will be leaving the blanket in supersaturated condition. At high flow rate of Pb-16Li through the blanket, helium is partially being removed from the blanket in dissolved form. For typical pressure of 1 MPa at the top of the blanket (at the Pb-16Li outlet from the breeding blanket), virtually all helium is dissolved at the flow rate of 10 000 kg/s. As the solution is then pumped into a part of the loop with lower pressure, helium bubbles are generated inside the duct.

author's email: Michal.Kordac@cvrez.cz

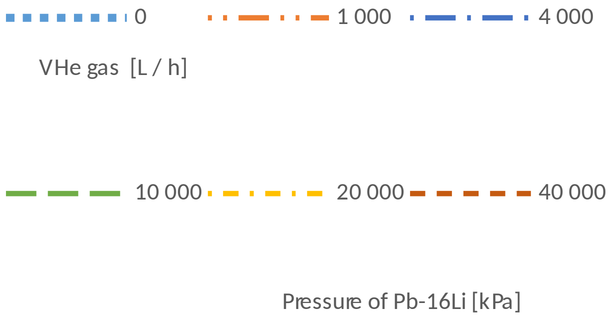

Fig. 2 Effect of pressure on helium evolution rate. Parameter: total flow rate of Pb-16Li.

Fig. 3 illustrates the same process from a standpoint of fixed position inside the blanket. Here, gas phase evolution rate is calculated for typical depths below the Pb-16Li surface as a function of Pb-16Li flow rate. The amount of gas phase being produced is practically independent of the Pb-16Li flow rate up to about 1 000 kg/s. At higher flow rates helium solubility limit is reached and the gas volume quickly drops to negligible values. For the flow rate of 10 000 kg/s, the first bubbles can be expected to generate only at depth of 7.75 m. The gas volume will grow as the hydrostatic pressure is decreased towards the surface, forming 13.1 L/h at depth of 5 m, 42.6 L/h at depth of 2.5 m and finally reaching the volume of 214.7 L/h of gas at the surface.

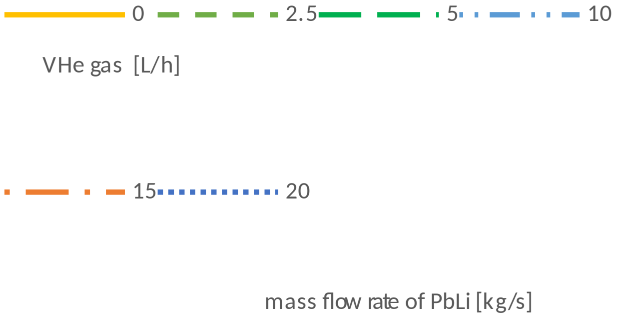

Fig. 3 Effect of mass flow rate of Pb-16Li on helium evolution rate. Parameter: depth below Pb-16Li surface.

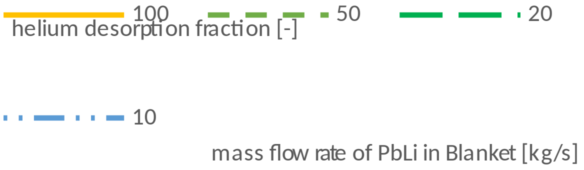

Fig. 4 Fraction of helium removal when equilibrium pressure (given in kPa) is reached.

At the same time, the very low helium solubility is in favour of high separation efficiency even for a single stage process, such as desorption in form of bubbles at the point of lowest pressure in the loop. Fig. 4 shows the effect of pressure in a helium separator. Even at atmospheric pressure, the efficiency is above 90% for mass flow rates of Pb-16Li up to 8 000 kg/s. With decreased pressure, the separation efficiency will be increased. This supports the assumption of negligible helium content in the Pb-16Li alloy entering the blanket.

The above considerations show the general situation for the DEMO blanket as a whole. Considering the vertical dimension of the DEMO tokamak it can be concluded, that the conditions for helium to stay dissolved or to form bubbles vary significantly between blanket modules. In order to make such detailed assessment, the blanket module distribution has to be taken into account.

3.2 Low flow rate of Pb-16Li

A blanket with primary coolant other than Pb-16Li, e.g. WCLL and HCLL, are designed with minimum flow velocities of the Pb-16Li alloy. The main portion of generated heat is removed with water or helium and the Pb-16Li loops are then used for transporting the generated tritium in the blanket towards the Tritium extraction system (TES) for tritium extraction and for maintaining the chemical regime inside the blanket. The breeding blanket is further sub-divided into individual modules as shown on Fig. 1 and is further subdivided into inboard and outboard segments with separate Pb-16Li supply piping. The total flow rate of Pb-16Li through the inboard segment is 6.7 kg/s, through the outboard segment 13.3 kg/s [13]. The total flow rate through the blanket is in this case 830 kg/s. The tritium (and also helium) production rate as well as local pressure in each module depends on the module position and its volume[14].

The tritium production distribution as obtained from Pereslavtsev et al.[14] is shown in Fig. 5 at the top. In the middle, calculated Pb-16Li saturation level at the outlet from each module is given. The supersaturation value is almost constant for all the modules with median of 6.5. The volume of gas produced within each module (at corresponding conditions) is plotted in Fig. 5 at the bottom. Here, an assumption is taken, that such

---

author's email: Michal.Kordac@cvrez.cz

supersaturation is sufficient to produce stable bubbles. Even though values in the range of 10 – 40 mL/h may not seem critical in comparison with the total volume of the blanket, gas pockets inside the modules will show long-term stability, decreasing the available volume of the breeder at the order of 3 – 12% after one year of operation (FPY).

Helium separation efficiency reached in a single stage operation for the conditions considered in this study is estimated to be approx. 99%, if the process is carried out at atmospheric pressure (see Fig. 4).

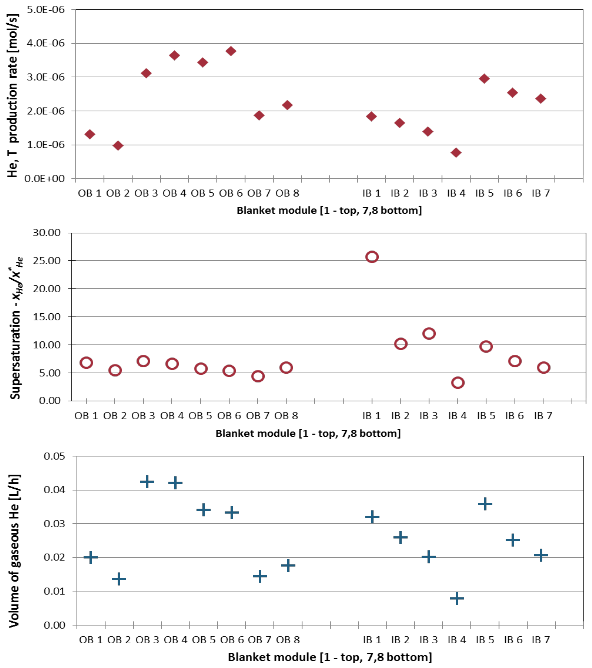

Fig. 5 Helium production rates (top), supersaturation (middle) and gas production rate (bottom) in modules of the blanket at low flow rate of Pb-16Li.

3.3 High flow rate of Pb-16Li

High flow rates of Pb-16Li are needed in the DCLL breeding blanket concept, where the Pb-16Li alloy has also function of a coolant for heat extraction. In this case, the total flow rate of Pb-16Li through the inboard segment is 183 kg/s, through the outboard segment 402 kg/s [15]. Due to different blanket geometry (mainly internals, not shown above), there is also different distribution of the tritium production rates as shown in Fig. 6 at the top.

The increased dissolution capacity of the high flow rate of Pb-16Li maintains the liquid below reaching full saturation in all modules as shown in Fig. 6 at the bottom. Median of the saturation value is only 0.38, which means that no stable clusters will be formed within the blanket modules. Nevertheless, once the solution of helium in Pb-16Li will get into a zone with reduced pressure, helium saturation will be reached along with a strong tendency towards bubble formation. Using the estimated value of the total flow rate for the DCLL blanket [15], 25 170 kg/s, this occurs at a depth of about 2.4 m assuming the cover gas pressure of 100 kPa.

Given the flow rate, the efficiency of helium separation is, according to Fig. 4, around 70% at pressure of 100 kPa. Cover gas pressure would have to be reduced below 15 kPa in order to increase the single stage separation efficiency above 95%.

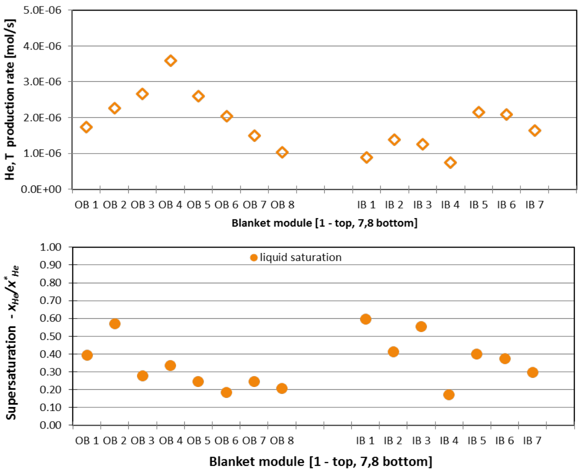

Fig. 6 Helium production rates (top) and liquid saturation (bottom) in modules of the blanket at high flow rate of Pb-16Li.

4. Conclusions

Helium produced as a by-product of tritium breeding should be also considered as one of the constrains for the DEMO breeding blanket design. The general analysis made shows the assessment of gas evolution is very sensitive to local conditions, such as pressure and Pb-16Li mass flow rate. Thus, an analysis of each of the breeding blanket concepts should be performed using up-to date geometry and flow conditions.

In the case of HCLL and WCLL blanket concepts it should be taken as one of the limiting concerns in the blanket design. The helium migration analysis presented here shows that supersaturation will probably occur at small flow rates of Pb-16Li. This will stabilize gas pockets and larger bubbles degrading the performance of the breeding blanket at the order of 3 – 12% after 1 FPY. In this case, the conditions are in favor of the simple helium separation with efficiency above 99%.

The blanket concept based on higher flow rate of Pb-16Li, DCLL, is more resistant against bubble formation in the modules. This is due to he larger amount of the Pb-16Li alloy available to remove helium from the blanket modules in dissolved form. More complex separation of helium will have to be designed as the current pressure conditions allow only 70% efficiency of the separation.

5. Acknowledgements

---

author's email: Michal.Kordac@cvrez.cz

This work has been carried out with 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 European Commission.

This work has been also supported by a grant no. MSMT-41274/2014-2 from Ministry of Education, Youth and Sports of the Czech Republic.

6. References

[1] U. Fischer, C. Bachmann, I. Palermo, P. Pereslavtsev, R. Villari, Neutronics requirements for a DEMO fusion power plant, Fusion Eng. Des. 98–99 (2015) 2134–2137. doi:10.1016/j.fusengdes.2015.02.029.

[2] L. Giancarli, V. Chuyanov, M. Abdou, M. Akiba, B.G. Hong, R. Lässer, et al., Test blanket modules in ITER: An overview on proposed designs and required DEMO-relevant materials, J. Nucl. Mater. (2007). doi:10.1016/j.jnucmat.2007.03.234.

[3] R. Conrad, Irradiation experiments on liquid tritium breeding material Pb-17Li in the HFR Petten, Fusion Eng. Des. 14 (1991) 289–297. doi:10.1016/0920-3796(91)90012-F.

[4] R. Conrad, M.A. Fütterer, L. Giancarli, R. May, A. Perujo, T. Sample, LIBRETTO-3: Performance of tritium permeation barriers under irradiation at the HFR Petten, J. Nucl. Mater. 212–215 (1994) 998–1002. doi:10.1016/0022-3115(94)90984-9.

[5] L. Batet, J. Fradera, E.M.D. Les Valls, L.A.A. Sedano, Numeric implementation of a nucleation, growth and transport model for helium bubbles in lead–lithium HCLL breeding blanket channels: Theory and code development, Fusion Eng. Des. 86 (2011) 421–428. doi:10.1016/j.fusengdes.2011.03.074.

[6] B. Meszaros, C. Bachmann, R. Kemp, G. Federici, Definition of the basic DEMO tokamak geometry based on systems code studies, Fusion Eng. Des. 98–99 (2015) 1556–1560. doi:10.1016/j.fusengdes.2015.06.097.

[7] M. Reungoat, PbLi technologies: DCLL PbLi loop – Preliminary design, (2015).

[8] M. Reungoat, PbLi technologies: HCLL/WCLL PbLi loop – Preliminary design, 2015.

[9] L. Batet, J. Fradera, E.M.D. Les Valls, L.A. Sedano, Numeric implementation of a nucleation, growth and transport model for helium bubbles in lead–lithium HCLL breeding blanket channels: Theory and code development, Fusion Eng. Des. 86 (2011) 421–428. doi:10.1016/j.fusengdes.2011.03.074.

[10] M.M. Gubzhokov, M.K. Ponegev, a B. Sozaeva, V. a Sozaev, Temperature dependences of wetting angles of steel 12Cr18Ni9Ti and ceramics by the melts with least additions of alkali metals, J. Phys. Conf. Ser. 98 (2008) 62028. doi:10.1088/1742-6596/98/6/062028.

[11] P. Fiflis, A. Press, W. Xu, D. Andruczyk, D. Curreli, D.N. Ruzic, Wetting properties of liquid lithium on select fusion relevant surfaces, Fusion Eng. Des. 89 (2014) 2827–2832. doi:10.1016/j.fusengdes.2014.03.060.

[12] P. Protsenko, A. Terlain, M. Jeymond, N. Eustathopoulos, Wetting of Fe–7.5%Cr steel by molten Pb and Pb–17Li, J. Nucl. Mater. 307–311 (2002) 1396–1399. doi:10.1016/S0022-3115(02)00988-1.

[13] J. Aubert, G. Aiello, A.L. Puma, A. Morin, Preliminary design of a Water Cooled Lithium Lead blanket concept for DEMO reactor, 2014.

[14] P. Pereslavtsev, R. Villari, DEMO Nuclear Analysis Handbook, EUROfusion, 2015. doi:EFDA_D_2LLZMA.

[15] A. Tincani, Preliminary design of DCLL LiPb loops, 2016.

---

author’s email: Michal.Kordac@cvrez.cz