Development of optimized hydrogen permeation sensors for testing the Korean test blanket module in the ITER

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1. Introduction

The need for a reliable sensor with quick response for the measurement of hydrogen isotopes concentration in the liquid breeder is evident and its conceptual design is the aim of this work for testing the liquid type test blanket module in the International Thermonuclear Experimental Reactor (ITER), which have been designed and developed in KAERI [1-5]. Among different possibilities, the choice of a sensor based on the principle of hydrogen isotopes permeation into a capsule of a suitable material seems to be, at least in principle, the simplest and the most reliable one.

2. Theory

2.1 The theory of hydrogen permeable membrane

As shown in Fig. 1, hydrogen permeation through metal membrane can be divided into the following five steps. Hydrogen molecules are absorbed selectively to the hydrogen permeable membrane. Then, large hydrogen molecules are separated in terms of the boundary. The diffusion of hydrogen atoms happens in the membrane by the difference of concentration. Hydrogen atom is recombinated by the hydrogen molecule at the opposite side. Finally, molecular hydrogen is released from the membrane.

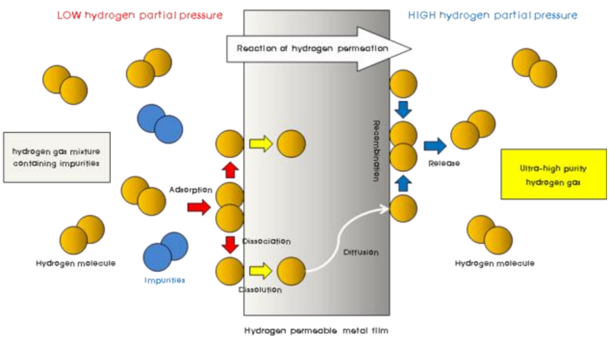

Fig. 1. The reaction of hydrogen permeation

2.2 Basics concepts on a hydrogen permeation sensor

In its simplest architecture, a hydrogen permeation sensor can be seen as a hollow capsule, permeable to hydrogen, immersed in a liquid metal where hydrogen is dissolved at a certain concentration C_L in equilibrium pressure P_{eq}. The permeation sensor can be operated in equilibrium or in dynamic mode. In the former, starting from vacuum condition, the pressure increases inside the capsule because of hydrogen permeation until the pressure P_{eq}, in equilibrium with the hydrogen concentration in liquid metal C_L, is reached. Then, the hydrogen equilibrium pressure measured inside the capsule is related to C_L by the Sieverts' law for a H/Pb-17Li system.

$$C_{L,H} = K_{S,L} P_{eq}^{0.5}$$

In the case of dynamic operation mode, the situation of the sensor is different because the inner volume of the capsule is continuously evacuated under the action of vacuum pump. Considering a pure diffusion regime through the membrane, the hydrogen flux at steady state is given.

$$J_{out,ss} = K_{S,M} D_m P_{eq}^{0.5} / s$$

H concentration is measured by the rate of its permeation through the capsule walls. The correct of operation of the sensor working in equilibrium mode depends only on a reliable determination of the Sieverts' constant in the liquid metal. Only the rate of the capsule pressurisation is affected by the permeation characteristics of the capsule, not the final pressure which is just the required measurement.

2.3 Candidate materials and technological requirement for application

The sensor must be able to quickly follow rapid change of the hydrogen concentration. This means that the capsule material should have a high permeability.

Among different materials with similar permeability values, those ones with higher diffusivity and lower Sieverts' constants are the most suitable. In this way, the hydrogen inventory in the capsule wall is minimized because of the lower Sieverts' constant. Furthermore, for materials with the same permeability, higher hydrogen diffusivity allows to reach more quickly

The capsule material must be chemically compatible, particularly from the point of view of corrosion, with pb-17Li in the temperature range of 450-550℃. Therefore, any pure metal or alloy containing Ni, Al, Ti, Zr, Cu in relevant percentage has to be avoided.

The capsule volume should be as small as possible, because the hydrogen inventory in the sensor must be negligible when compared to the hydrogen inventory in the liquid metal. The dead volume of the permeation sensor must be as small as possible, in order not to increase too much time necessary to obtain the hydrogen pressure equilibrium between the capsule and liquid metal phase[6].

3. Design of the optimized sensor

3.1 Selection of the sensor materials

Niobium, Tantalum and Vanadium seem to be possible candidates for the permeable capsule chamber wall, considering that, despite their high Sieverts' constant, they have relatively high hydrogen diffusivity. As the best material of the capsule, we decided to use Armco iron, in which the easier welding and machining of this material was considered.

3.2 Design of the sensor geometry

To determine the geometry of the sensor, this case is based on the sensor which used in TRIEX facility, which have been developed in EU for testing the tritium extraction for the ITER[7]. The sensor in the facility is shown in Fig. 2.

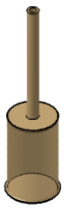

Fig. 2. The sensor which has cylinder geometry

Two preliminary designs of the sensor capsule, devoted to reduce the 'total sensor volume/permeation surface' ratio have been developed and shown in Fig. 3. In the left of Fig. 3, the internal volume reduction is obtained by filling the capsule with an adequate material in which hydrogen is not soluble[8]. To reduce the internal volume we selected tungsten which is known for as a non-permeable hydrogen material[9]. Internal volume reduction is obtained using an annular geometry for the capsule, as shown in the right side of Fig. 3.

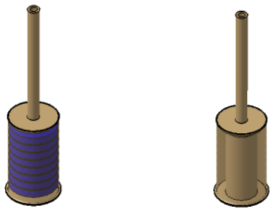

Fig. 3. The sensors to reduce the dead volume.

3. The planning of experiments

For optimal performance in order to develop a sensor apparatus used for these measurements is shown schematically in Fig. 5. A known concentration of hydrogen and argon gas inside the chamber will be placed hydrogen sensor. The SS tube containing the capsule was isolated from the pump, and a known amount of hydrogen was admitted. When the sensor is operated in the equilibrium mode, the vacuum pumping system is not active during the test, but will be used to realize the initial vacuum and to remove permeated hydrogen at the end of each experimental run.

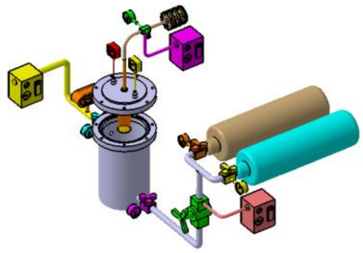

Fig. 5. The Schematic diagram of the experimental device.

4. Conclusions

In order to investigate the performance of hydrogen permeation sensors installed in this experimental device, they are made of Armco iron with a three different geometry and will be operated in equilibrium mode. In order to maximize the performance of the sensor, it is important to minimize the dead volume inside the sensor.

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