THEORETICAL AND EXPERIMENTAL EVALUATION OF THE WINDOWLESS INTERFACE FOR THE TRASCO-ADS PROJECT

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Abstract

TRASCO-ADS is a project in which INFN, ENEA and Italian industries work on the design of an accelerator driven waste transmutation sub critical system. TRASCO is an Italian acronym for Transmutation (TRASmutazione) of Waste (SCOrie). One of the most critical aspect of an Accelerator Driven System (ADS) is the interface between the UHV environment of the accelerator and the pressurize system (about 1 bar Pb-Bi eutectic at 400°C) of the reactor core. The 'window' is the physical interface between the two environments. Thermo-mechanical and radioprotection issues pointed out that the window is a critical issue. The windowless interface consists of a system where the reactor and the linac are separated just by a progressive dynamic pumping system that connects the vacuum of the linac accelerator and the coolant flow of the reactor core. This paper reports the theoretical and experimental work that is running to investigate the gas and vapors load and their interaction in the interface system. Vacuum requirement and radioprotection issue need an accurate evaluation of the composition and total load of the gas and vapors from the reactor core. The final objective of this work is the dimensioning and the validation of the vacuum system of the interface region.

1 INTRODUCTION

Accelerator Driven System (ADS), i.e. sub critical reactor driven by an external neutron source generated by high energy protons impinging on heavy nuclei, are in progress in several countries following the Rubbia proposal [1]. Such systems aims to fission transuranics and to transmute selected long-lived fission fragments. The Italian TRASCO program [2] aims to study the physics and to develop the technologies needed to design an ADS for nuclear waste transmutation. TRASCO is the Italian acronym for Transmutation (TRASmutazione) of Waste (SCOrie). The proposed R&D program investigates all the ADS main subsystems such as accelerator [3], window/target and sub-critical reactor.

2 TRASCO - WINDOWLESS

Two target options are foreseen for the TRASCO configuration: the hot window and the windowless one. This paper refers specifically to the windowless configuration where there is no physical separation in between the Lead Bismuth Eutectic (LBE) free surface and the ultra high vacuum condition of the proton beam tube. The proton beam will deposit on the LBE about 80% of its power and the hydraulic circulation has to be carefully designed in order to remove, with the maximum efficiency, the deposited energy maintaining the free surface temperature around 450°C.

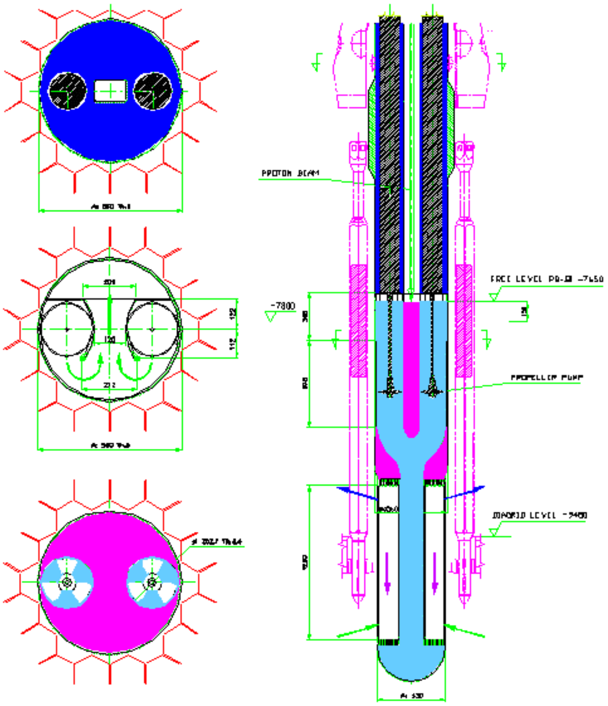

Fig. 1 - Conceptual drawing of the windowless configuration. The center-left picture shows the interaction region cross section.

Vacuum system must ensure both the excellent vacuum conditions required for the beam pipe and the protection of the accelerator from vapors and gases coming from the LBE. The main source of vapors is the LBE itself (more then 10 kg/year); moreover spallation nuclear reactions will produce Hg, Po and H_2. Water vapor will be produced during the oxidation control of the LBE and of the steel surfaces.

3 VACUUM SYSTEM DESIGN

The design of the windowless solution vacuum system has to deal with complex geometries, surfaces at different temperatures, vapors condensation and gas dynamics. A numerical approach has been chosen and a measurement campaign has been carried out to validate it and to tune the free parameters.

3.1 Numerical approach

Usually, vacuum science and technology faces the problem of computing the partial pressure distribution in a vacuum system. Gas flows are derived from partial pressures using the kinetic theory of gases. Gases typically are released from the walls of the pipes due to desorption phenomena and not from a liquid phase and their partial pressures are easily measured by means of standard manometers. On the contrary, partial pressures of LBE components cannot be properly carried out using ordinary manometers; furthermore LBE is not in thermodynamic equilibrium with its own vapor so vapor pressure is not unequivocally defined.

We decided to develop a suitable numerical model to directly compute the distribution of gas fluxes in the interface pipeline. Due to the rather complex geometry of the system, the method of angular coefficients has been chosen [4]. A finite-element method is used to discretize the system that is divided in elements where the density of the total emitted molecular flux (ν) is assumed as a constant. For each mesh element i we can write:

$$\nu_i = \nu_{0i} + (1-\varepsilon_i)\nu_{inc\,i}$$

where ν_{0i} is the molecular flux density generated by the i-th surface (e.g. the thermal gas desorption flux); ν_{inci} is the flux density incident on the elementary area and ε_i is the adsorbed fraction of incident flux, accounting different physical phenomena as the reflection of molecules on the surface, the desorption of gas stimulated by the impinging molecules, the sticking of molecules on the surface and the condensation effect.

We can write ν_{inci} as:

$$\nu_{inc\,i}\, dF_i = \sum_{j=1}^{n} \varphi_{j->i}\, \nu_j\, dF_j$$

where dF_j is the mean angular coefficient from the j-th surface to the i-th surface and n is the number of elements. Using a well-known property of the view factors, we can write:

$$\nu_{inc\,i} = \sum_{j=1}^{n} \varphi_{i->j}\, \nu_j$$

$$\nu_i = \nu_{0i} + (1-\varepsilon_i)\sum_{j=1}^{n} \varphi_{i->j}\, \nu_j$$

We obtain a system of n unknowns consisting in the fluxes emitted from each elementary surfaces. So the adsorbed fluxes can be calculated easily as:

$$\nu_{ads\,i} = \varepsilon_i \sum_{j=1}^{n} \varphi_{i->j}\, \nu_j$$

View factors are calculated with the software tool ANSYS 6.0[5], able to solve thermal radiation problems that require the evaluation of the same view factors needed in our model.

3.2 Experimental set up

First an LBE ingot (99.99 %) was melted under Ar atmosphere and then deoxidized with Ar-H_2 mixture (5% H_2) at 350°C, controlling the dew point of the outgoing gas. Two different experimental set up have been arranged to test and validate the numerical tool previously discussed.

One system is dedicated to the LBE weight loss measurement (gravimetric method): the sample was heated at 450°C and 560°C and allowed to evaporate for 15 h and then weighed to evaluate the amount of alloy lost by evaporation. Sensitivity is better then 1 mg.

The second set up consists of an UHV oven (pressure < $1\cdot10^{-6}$ mbar @600°C), connected to a 2 m long tube (63 mm I.D., temp. up 200°C). Two thickness monitors, used as microbalances, are fitted in the vacuum pipe and can be inserted (one at a time or both) at 685 mm (z_1) and 1685 mm (z_2) distance over the LBE liquid surface, without breaking the vacuum. They monitor the deposition rate with 0.1 nm resolution over an area of 50 mm^2. Microbalance temperature can be controlled up to 175°C. Total and partial pressure are monitored by two ion gauges and a RGA (residual gas analyzer).

An atomic absorption spectrometer is used to analyze the chemical composition of the vapor condensed on the microbalance quartzes and on the gravimetric flask.

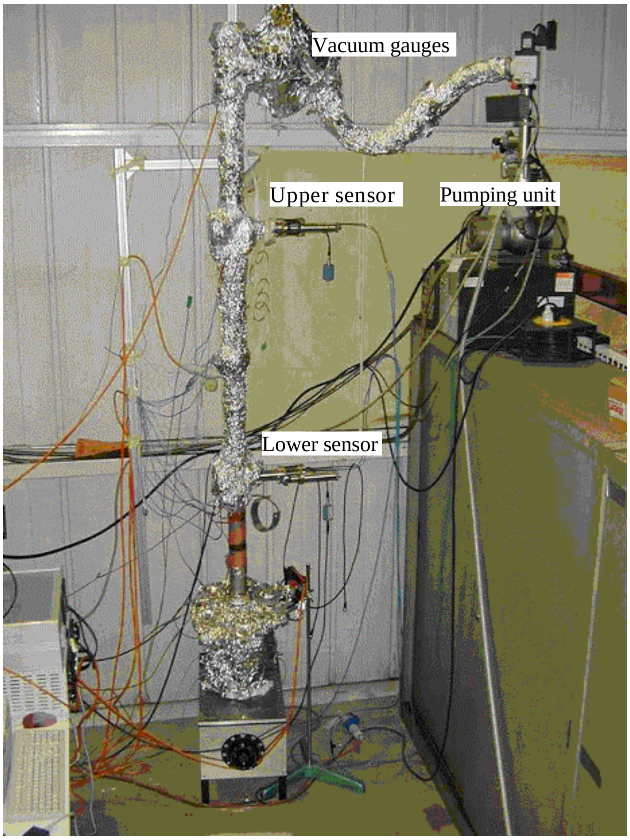

Fig.2 – Experimental setup with indicated sensor position, oven, pumping system and vacuum gauges.

3.3 Experimental results

A single microbalance (upper or lower) was used during the experiments to measure the deposition rate. In some experiments both microbalances were used to study the shadowing effect of one microbalance with respect to the other. We expect the ratio R between the deposition rate $\nu_{ads,S}(T,z_2)$, measured with the upper balance, and $\nu_{ads,S}(T,z_1)$, with the lower one, is independent on the LBE evaporation rate while it depends only on geometrical factors and on the free parameter ε.

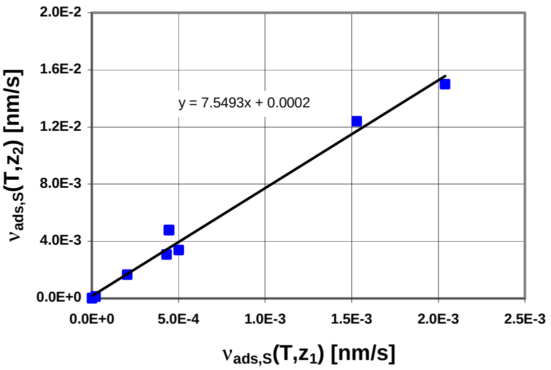

Fig. 2 – $\nu_{ads,S}(T,z_2)$ $\nu_{ads,S}(T,z_1)$ experimental value at different LBE temperature T: the constant slope is the ratio R.

An evaluation of the ratio R from the experimental values measured at different LBE temperatures is given in fig. 2. The value obtained is R = 7.54, independent on the LBE temperature. The measured value R ≅ 7.54 correspond to a calculated value of ε ≅ 0.27 that correctly describe all the experimental data with the tube at room temperature. Measurements with the tube at higher temperature (175°C, > LBE melting point, m.p.), using only the upper microbalance, have indicated lower deposition rates than the one measured with the tube at room temperature (an examples is plotted in figure 3).

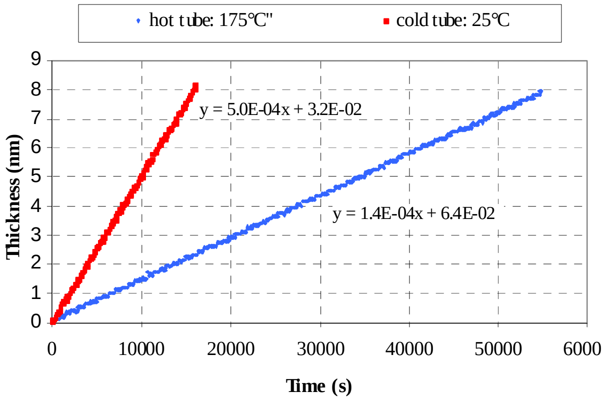

Fig. 3 – Comparison between deposition rate on the upper sensor with cold and hot tubes.

Therefore we have estimated a higher value for the ε coefficient indicating a higher absorbed fraction of the impinging molecules.

4 CONCLUSIONS

A suitable numerical tool has been developed to study the gas and vapor dynamics for the windowless interface of TRASCO. This tool could be used to design the complex vacuum system for pumping the interface region where both vapors and gases are present and the boundaries surfaces will have different temperatures.

This new tool needs experimental data on liquid LBE at very low pressure as in an UHV environment because data are not available in literature. For this reason, an experimental setup has been built that allows measuring weight loss and evaporation rate from free surface of liquid LBE at different temperatures. The free parameter for the dynamics of the LBE vapor in the tube is mainly the adsorption constant ε that influences strongly the vapor dynamics in the system. From the evaporation measurements on the microbalances, we computed it to be 0.27 with the tube at room temperature. Once ε has been set, we have evaluated the evaporation rate and compared it with the literature data: a good agreement with lead data has been obtained, that disagrees with Raoult law [6], [7].

Measurement with hot tubes (175°C, τ > LBE m.p.) indicates an absorption coefficient ε probably higher than the one at room temperature. Nevertheless the sensitivity of the upper microbalance is too low for a correct evaluation of the ε coefficient. For the future a better estimation will be achieved using the lower sensor

A preliminary measurement of the condensed fraction composition indicates that it differs from the one of the LBE: Bi concentration is 66% instead of 55.5%.

The future plan is to study in deeper details the properties of liquid LBE in UHV condition and to continue the validation of the numerical model, checking the validity of the Raoult law for LBE at different temperatures, in view of a complete design of the windowless interface between linac and reactor.

5 REFERENCES

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