

# Vapor condensation study for HIF liquid chambers

P. Calderoni\*, A. Ying, T. Sketchley, M.A. Abdou

*Mechanical and Aerospace Engineering Department, UCLA, 44-114 Eng IV, 420 Westwood Plaza, Los Angeles, CA 90095-1597, USA*

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## Abstract

This paper presents the experimental study of transient cooling and condensation of the prototypical material flibe under conditions relevant to Heavy Ion Fusion (HIF) power plants. Superheated vapor is generated by a high-current, pulsed electrical discharge over a pool of liquid flibe. The excited vapor expands inside a temperature-controlled chamber designed to scale the initial density of the generated vapor, the initial energy density and the surface area available for condensation, considering HYLIFE-II as the reference design. Clearing rates are evaluated from the measured pressure history. Mass spectroscopy is used to characterize the composition of the residual gases. SEM analysis of material deposited on witness plates is also presented, showing that interface phenomena during the initial expansion phase depend on the orientation of the condensation surface relative to the gas velocity. The results show that chamber clearing can be characterized by an exponential decay with a time constant of 6.58 ms. However, the equilibrium pressure is one order of magnitude higher than the desired HIF base pressure because of the presence of non-condensable impurities dissolved in the material available for the experiments. If the exponential decay is applied to the pressure range of the reference design, the resulting period for chamber clearing is 60 ms. The conclusion is that condensation rates of flibe vapor are sufficiently fast to allow HIF power plants repetition rates, and that the main issue for flibe vapor condensation lies in the control of the impurities dissolved in the salt.

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## 1. Introduction

This paper presents the study of vapor condensation for the assessment of chamber clearing

in Heavy Ion Fusion (HIF) power plants. The HYLIFE-II concept is considered as reference design for effective scaling of experimental parameters [1]. Vacuum conditions must be restored after each fusion pulse to efficiently couple the energy drivers with the target. Since economic assessment of energy generation impose considering repetition rates of few pulses per second, the

\*Corresponding author. Tel.: +1 310 206 2755;  
fax: +1 310 825 2599.

E-mail address: [patcal@fusion.ucla.edu](mailto:patcal@fusion.ucla.edu) (P. Calderoni).

study of the transient condensation of the superheated vapor generated by the absorption of X-rays and ions emitted in the fusion event becomes a key feasibility issue. Since chemical processes such as recombination and diffusion play an important role in determining the condensation rates, it is necessary to investigate prototypical materials if conditions relevant to HIF power plants must be met [2]. The results described in this paper are obtained using the prototypical composition of the binary salt composed of lithium fluoride and beryllium di-fluoride, usually referred to as flibe (33%  $\text{BeF}_2$ , 66%  $\text{LiF}$  or  $\text{Li}_2\text{BeF}_4$  in moles).

The experiments are performed in a facility designed to generate an electrical discharge in a vacuum chamber with typical peak currents of 100 kA and periods of 100  $\mu\text{s}$  [3,4]. Although the mechanism for excited vapor generation (resistive and radiative heating) is different from that in HIF chambers [5,6], the short time scale of the generation process ensures that relevant conditions are met, if the initial conditions for the condensation process are the same [7]. The expansion chamber is designed to scale the initial density and the initial energy density of the generated vapor (Table 1). The surface area available for condensation in the experiments is minimized in order to reproduce the HIF chamber condensation process as close as possible.

## 2. Experimental set-up

The vacuum chamber is a six-way cross that is electrically and thermally insulated by ceramic breaks (Fig. 1).

The cathode, a 0.3 m tungsten rod, is inserted from the top and is connected to the negative side of a large bank of capacitors (640  $\mu\text{F}$ , 154 kJ maximum stored energy) through a high-current switch and a conditioning circuit [3]. The lower port is used to insert the crucible that holds the liquid flibe, which is melted inside a 0.0127 m diameter and 0.0127 m deep cavity by a high-density cartridge heater in a separately pumped volume. The flibe pool and the crucible act as the discharge anode (maintained at ground potential). A piezo-resistive pressure sensor is mounted on

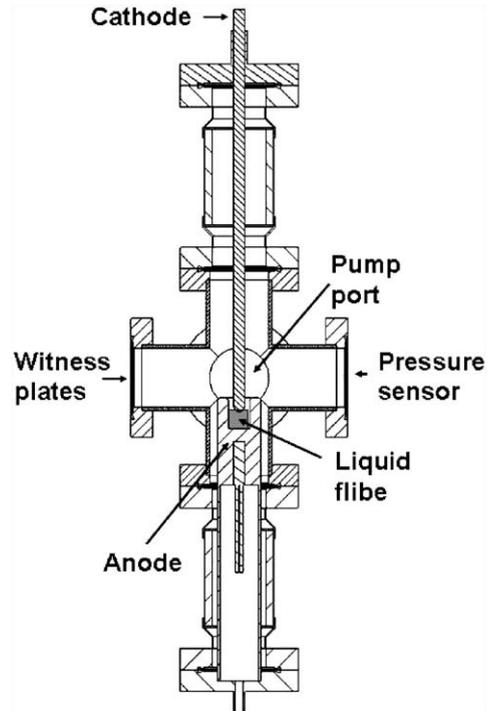


Fig. 1. Scheme of the experimental set-up.

Table 1  
Scaling the experiments to HYLIFE-II parameters

	HYLIFE-II	Flibe exp
Chamber volume ( $\text{m}^3$ )	280	$4 \times 10^{-4}$
Estimated total mass of vaporized material (kg)	4	$4 \times 10^{-5}$
Initial particle density ( $\text{m}^{-3}$ )	$9 \times 10^{23}$	$5 \times 10^{23}$
Estimated initial vapor temperature (eV)	1	1
Total energy density available for surface vaporization (J/kg)	$7.85 \times 10^6$	$7.5 \times 10^6$
Surface available for condensation ( $\text{m}^2$ )	1100	$4.2 \times 10^{-2}$

one of the four remaining ports. The high resonant frequency and low sensitivity to acceleration allows recording the pressure history with microseconds time resolution and adequate noise suppression. A capacitive manometer with milliseconds time resolution is mounted on the facing port before the valve that connects the chamber to the turbomolecular pump. A residual gas analyzer is also connected before the valve. The remaining ports are used to mount two flanges that support two sets of stainless steel witness plates. Each support is machined to accommodate two witness plates oriented  $90^\circ$  with respect to each other. Although not exactly a point source, the vapor generated in the arc discharge can be assumed to expand initially along the radius of hemisphere with the center corresponding to the liquid flibe surface. One of the witness plates is then mounted with the surface tangential to the vapor velocity direction, while the second plate surface intercepts it perpendicularly. The characteristics of the electrical discharge are recorded with a precision current-monitoring transformer and a high-voltage divider.

The flibe material used in the experiments has been supplied by Idaho National Engineering and Environmental Laboratory as a crystalline salt, and used as received. The experiments with the IFE prototypical material flibe are complicated by the toxicity of beryllium. Three experiments involving flibe have been performed for the purpose of this work, two at different energy levels and the chamber walls have been uniformly heated to  $300^\circ\text{C}$  and one with the chamber walls at  $500^\circ\text{C}$ . The confidence in the repeatability of the measurements acquired testing teflon ( $\text{CF}_2$  polymeric chain) and lithium fluoride (LiF) [3,4] ensures that the collected data are sufficient to reach the conclusions presented in this paper for the feasibility study.

### 3. Results and discussion

#### 3.1. Chamber clearing rates

Pressure data measured during the experiments with the chamber at the uniform temperature of  $500^\circ\text{C}$  and  $300^\circ\text{C}$ , respectively, are shown in Fig. 2.

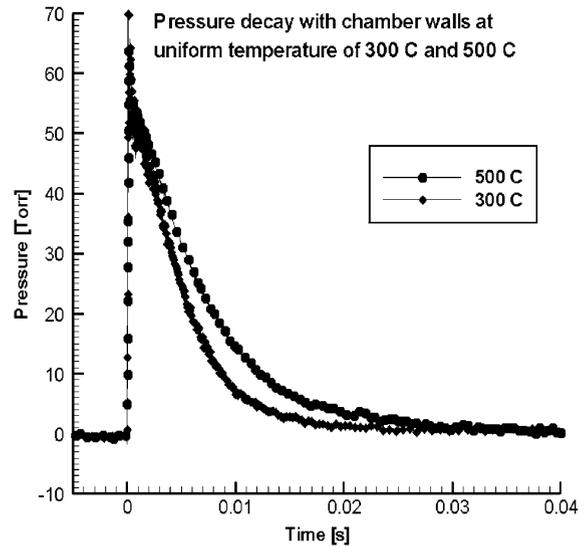


Fig. 2. Measured pressure decay for different chamber wall temperatures.

The energy coupled in the discharge was the same for both experiments (2.56 kJ), thus the same amount of material is vaporized and the same initial pressure peak measured. The pressure decay is well fit by an exponential curve and characterized by a time constant which represents the period necessary for the pressure to fall from its peak value to about 36% of the same, or  $1/e$  with the peak referenced to 1. The decay time constant at  $300^\circ\text{C}$  is 4.27 ms, while at  $500^\circ\text{C}$ , it is 6.58 ms. The latter is the reference value for HIF systems, as the structures in contact with the liquid must be constantly maintained at a temperature above the melting point of flibe, which is  $460^\circ\text{C}$ . The data recorded during the lower energy experiment (1.44 kJ) show a lower peak (43 Torr) but a decay constant similar to the high-energy case at the same temperature (4.22 ms). To compare the experimental data with numerical simulations of chamber clearing processes in HYLIFE-II [8], the measured pressure can be translated in terms of particle density, assuming that the vapor is in equilibrium with the liquid and follows the ideal gas equation of state [9]. The range covered by the experiments corresponds to a peak of about  $5 \times 10^{17} \text{ cm}^{-3}$ , and an equilibrium value of about

$2 \times 10^{15} \text{ cm}^{-3}$ . Mass spectroscopy of the residual gases after the condensation process shows that the condensation of  $\text{LiF}$  and  $\text{BeF}_2$  is complete, and that the high value of the density in equilibrium is due to non-condensable species dissolved in the flibe. About 56% of the remaining vapor is composed of hydrogen. Another 26% is due to the light hydrocarbon products of C and H atoms recombination (ethylene and ethane), and 12% due to recombination of carbon with oxygen to form  $\text{CO}_2$  and  $\text{CO}$ . Mass spectroscopy analysis during steady-state heating of the liquid material from 460 to 700 °C confirmed that the liquid flibe itself is the source of the impurities.

During one cycle of the HYLIFE-II power plant, the density in the chamber varies from the initial density of  $9 \times 10^{17} \text{ cm}^{-3}$  to  $3 \times 10^{13} \text{ cm}^{-3}$ , which is a conservative level, considered acceptable for ion beams propagation. If the measured decay constant of 6.58 ms is considered to be valid in the whole range, the clearing period for HYLIFE-II is calculated as 68 ms, which is substantially lower than the 200 ms limit imposed by the 6 Hz repetition rate of the power plant. Thus, the main conclusion of this work is that flibe vapors clearing for IFE chambers involving a liquid protection scheme is compatible with the high repetition rates dictated by the economical attractiveness of the power plant.

### 3.2. SEM analysis

SEM microscopy and EDX surface composition analysis of the material deposited on the witness plates supports the finding that film condensation is partially or completely inhibited on surfaces perpendicular to the vapor velocity. It also confirms that film condensation during the first expansion phase (first millisecond) coexists with in-flight condensation (and subsequent particle deposition) of the vapors in the form of sub-micron sized droplets in the later stages of the process. Since the initial expansion phase is characterized by a highly directional velocity, the film forms only on surfaces tangential to the hemisphere radial direction (Fig. 3). The area

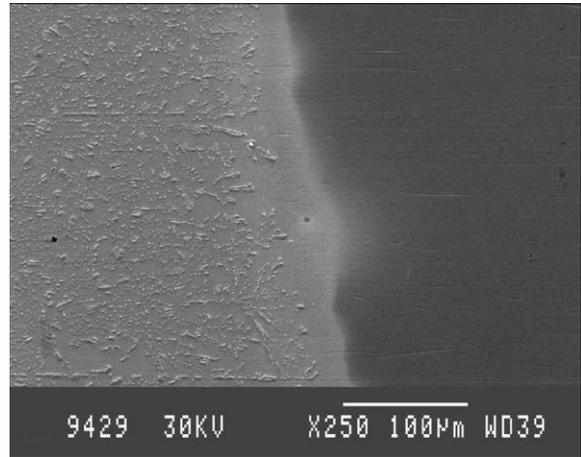


Fig. 3. 250 × SEM picture of tangential plate.

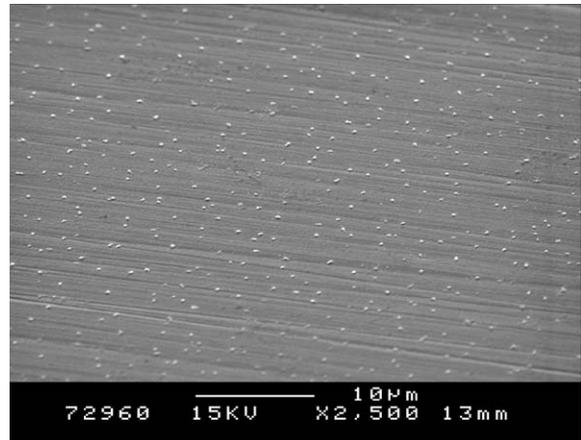


Fig. 4. 2500 × SEM picture of perpendicular plate.

without the deposited film was covered by a washer during the experiment.

After multiple reflections on the chamber walls, the vapor velocity becomes relatively uniform and in-flight condensation results in droplets that carry a uniform velocity, thus depositing on all witness plates (Fig 4).

The condensed film does not form on the perpendicular plate because its center is a stagnation point for the velocity field. The vapor slows down above the plate, its temperature increases and the

heat is transferred by convection and radiation to the metal surface. Because of the slow response of heat conduction, which is the dominant mechanism of heat transfer inside the metal, the temperature of a thin layer on the metal surface increases sharply. A simple engineering evaluation of the process can be done by considering the parameters reported in Table 1 for the generated vapor and the chamber geometry, which refer to a simplified uniform initial condition. During the first millisecond, the thermal penetration depth can be estimated as  $\delta = \sqrt{\alpha t}$  for the stainless steel chamber wall, in this case  $58 \mu\text{m}$  ( $\alpha$  is the thermal diffusivity of the material and  $t$  the period under consideration). The critical point of a substance can be considered as a simple estimate of the temperature below which two-phase equilibria between the vapor and liquid phases are possible. Although it has never been measured, the critical temperature for flibe has been estimated to be 4500 K [10]. As a conservative approach, we can assume that it is necessary for the metal surface to reach such a temperature to inhibit vapor condensation during the initial expansion. The amount of energy per unit area absorbed by the metal layer due to the temperature increase is  $E = \delta \rho C_p \Delta T$ , which corresponds in this case to  $8.1 \times 10^5 \text{ J/m}^2$ . The necessary power averaged over the period under consideration is  $8.1 \times 10^8 \text{ W/m}^2$ , and has to be supplied by the surface heat flux due to radiation and convection. The radiative flux generated by the superheated vapor in its initial, uniform state at 1 eV is  $q = \varepsilon \sigma (T_{\text{gas}}^4 - T_s^4)$ , in this case  $3 \times 10^8 \text{ W/m}^2$ . If we consider only a small increase in the gas temperature because of the stagnant flow, and we add the contribution of heat convection, we can conclude that the conditions are such that heating of the thin layer of the metal surface will locally inhibit the condensation process near the stagnation region.

#### 4. Conclusions

We measured experimentally the condensation rate of superheated flibe vapor in conditions relevant to HIF power plant studies. The relevance of the experimental results is ensured by scaling

analysis that considers the HYLIFE-II as the reference design. The measured vapor density decays exponentially with a time constant of 6.58 ms in the range of validity of the experiments—between  $0.5 \times 10^{18}$  and  $2 \times 10^{15} \text{ cm}^{-3}$ . The upper limit is comparable with that of the density cycles between pulses of the HYLIFE-II chamber, while the lower limit is higher than the reference base density because of the presence of non-condensable gases dissolved in the flibe material available for the experiments. The results show that impurity control and purification technology of the molten salt become crucial issues for applications that require recovery of vacuum conditions in the  $10^{13} \text{ cm}^{-3}$  range. However, if the decay constant measured in the experiments is extrapolated to the expected density cycles of HYLIFE-II, the vapor clearing rate is estimated as 68 ms, which is well below the required 200 ms for the reference 6 Hz repetition rate. A second original finding comes from the post-analysis of witness plates mounted inside the expansion chamber. The results suggest that for flow conditions characterized by high kinetic energy, flibe vapor condensation is partially inhibited on surfaces normal to the initial vapor expansion. Numerical modeling of the phenomena at the solid–vapor interface are under way to simulate the experimental condition and support the results.

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