

THIN LIQUID WALL BEHAVIOR UNDER IFE CYCLIC OPERATION

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ABSTRACT

An inertial fusion energy (IFE) wetted wall configuration provides the advantage of a renewable armor to accommodate the threat spectra. Key issues are the re-establishment of the thin liquid armor and the state of the chamber environment prior to each shot relative to the requirements imposed by the driver and target thermal and injection control.

I. INTRODUCTION

A wetted wall combines the strong features of a solid wall (robust mechanical design and efficient energy recovery) with the advantages of a renewable armor to accommodate the X-ray and ion threats. In this configuration, part of the thin liquid film armor evaporates under the incident X-ray and ion energy deposition fluxes. Key issues are the re-establishment of the thin liquid armor and the state of the chamber environment prior to each shot relative to the requirements imposed by the driver and target thermal and injection control. In determining the conditions of the chamber gas and/or vapor prior to each shot it is important to consider the possible presence of aerosol. The major processes involved in chamber clearing are those providing the source terms for aerosol formation (both from the high power deposition at the wall and from subsequent in-flight re-condensation), the aerosol behavior between shots, and condensation to the wall.

These issues were analyzed in detail as part of the ARIES-IFE study [1] for different driver and target combinations. The study considered both direct drive and indirect drive targets but this paper focuses on the more challenging indirect drive target case where about 25% of the 458 MJ yield (assumed for the example case [2,3]) is in the form of X-rays (as compared to only ~1% for a typical direct drive target).

This paper summarizes the key results from the study. First, an assessment of film re-establishment and coverage is presented, including issues linked with normal and tangential replenishment such as film

detachment and droplet formation. Next, a scoping analysis of condensation under IFE conditions is presented. An analysis of aerosol formation and behavior is then summarized including the characterization of source terms. Finally, estimates of the vapor and aerosol mass remaining in the chamber prior to each shot are compared to driver requirements as an illustration of possible operating parameter design windows for such a class of IFE chamber.

Pb and flibe have been considered in recent IFE concepts, such as the PROMETHEUS wetted wall concept [4] and the HYLIFE-II thick liquid wall concept [5], and are considered as example liquids in the analysis presented here.

II. FILM DYNAMICS

Experimental and numerical studies have been conducted to examine the fluid dynamic aspects of thin liquid film protection systems with either radial injection through a porous first wall (hereafter referred to as the "wetted wall" design) or forced flow of a thin liquid film tangential to a solid first wall (hereafter referred to as the "forced film" design). Previous work on liquid film flow on vertical and upward-facing surfaces has shown that for all IFE coolants of interest with surface contact angles ranging from 0° to 90°, dry patch formation can be prevented by maintaining the film thickness and flow velocity above ≈ 1 mm and 1 m/s, respectively [6,7]. Hence, for both the wetted wall and forced film designs, our efforts have focused on examining the liquid film behavior on the downward-facing surfaces (upper section) of the reactor cavity, where virtually no work has heretofore been done.

Among the critical questions needed to establish the viability of the wetted wall concept are: (1) Can a stable liquid film be maintained on the upper section of the chamber? (2) Can the film be reestablished over the entire cavity surface prior to the next target explosion? and (3) Can a minimum film thickness be maintained to prevent dry patch formation and provide adequate protection during the next target explosion. To this

end, a model has been developed and analysis performed to examine the effect of key variables on the transient three-dimensional topology of the film free surface, the frequency of liquid drop formation and detachment, the size of the detached droplets, and the minimum film thickness prior to droplet detachment [8]. A preliminary experimental investigation aimed at validating the model has also been performed. Example results for the evolution of the free surface for a liquid lead film on a horizontal downward-facing surface are shown in Figure 1. The film is assumed to be at 700 K with an initial thickness of 1.0 mm and an injection velocity of 1.0 mm/s; a random initial perturbation with maximum amplitude of 1.0 mm is applied at the beginning of the transient. These results suggest that droplet detachment occurs nearly 0.38 s after the initial perturbation is imposed.

A parametric analysis has been used to develop “generalized charts,” which make it possible for system designers to establish “design windows” for successful implementation of the wetted wall concept [8]. Overall, the results suggest that: (i) liquid film stability may impose a limit on the minimum repetition rate in order to avoid liquid “dripping” into the chamber between shots; and (ii) a minimum injection velocity will be required to prevent the film thickness from decreasing below a designer-specified minimum value dictated by wall protection requirements.

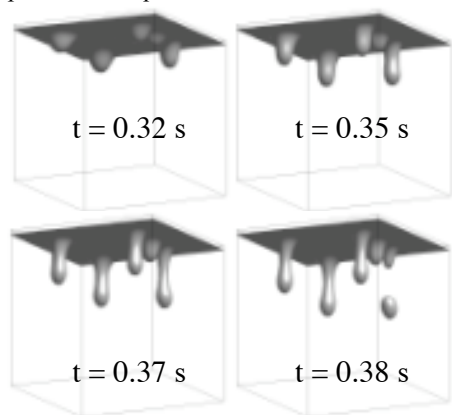


Figure 1 Evolution of a Pb film surface on a downward facing first wall with random initial perturbation.

For the forced film flow wall protection concept, film detachment under the influence of gravity is most likely to occur on the downward facing surfaces in the upper part of the reactor chamber. Film detachment and uncontrolled “fall-out” would likely interfere with beam propagation and/or target injection; it would also negate the protective function of the film. Hence, an experimental study has been performed to determine the

effect of various design and operational parameters on the film detachment distance downstream of the introduction point for downward-facing flat surfaces with various inclination angles. Experiments were conducted for both wetting and non-wetting surfaces with different initial film thickness (1.0 to 2.0 mm), initial film injection velocity (1.9 to 11.0 m/s), and inclination angle (0° to 45°).

Figure 2 provides typical results for the detachment distance normalized by the initial film thickness, (x_d/δ) , as a function of the Froude number, $U/(g \sin \theta \cos \theta)^{1/2}$, for both wetting (glass) and non-wetting (Rain-X® coated) horizontal downward facing surfaces. Here U is the initial film velocity, g is the gravitational acceleration and θ is the inclination angle. Similar data for other inclination angles may be found in reference [9]. The data suggest that the normalized detachment distance strongly depends on the Froude number and surface characteristics (i.e. wettability). The data shown in Figure 2 for a non-wetting horizontal surface provide a lower bound for the detachment distance. These data allow the designers to establish the maximum spacing between film injection and liquid return points along the cavity surface to avoid film detachment.

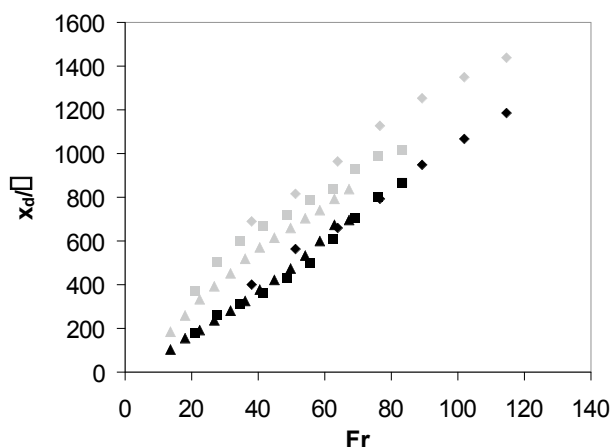


Figure 2 Variation of the normalized film detachment distance with Froude number for horizontal downward-facing surfaces [pale symbols=wetting surface; dark symbols=non-wetting surface; δ = 1.0, 1.5, and 2.0 mm (diamonds, squares, and triangles, respectively)].

Experiments have also been performed to examine the behavior of thin liquid films flowing around cylindrical obstacles, typical of beam and target injection ports. These results indicate that the presence of such obstacles will pose significant challenge to the designers, inasmuch as the disrupted film may directly interfere with the intended function of the port (viz.,

beam propagation or target injection). Hence, efforts are currently underway to examine the behavior of thin films flowing past “streamlined” obstacles.

III. CHAMBER CONDITIONS

Pre-shot chamber conditions must satisfy driver and target requirements. In addition to the conditions of the chamber gas/vapor governed by evaporation and film condensation, the possible presence of aerosol must be considered. The major processes involved are those providing the source terms for aerosol formation (both from the high power deposition at the wall and from subsequent in-flight re-condensation), and the aerosol behavior between shots.

III.1 Film Condensation

A characteristic condensation time based on condensation rate and corresponding vapor mass in the chamber was used to estimate the time required for film condensation to clear the chamber as a function of the chamber fluid vapor pressure and temperature [10]. This characteristic time was found to be independent of the vapor pressure until the pressure starts approaching (within about one order of magnitude) the saturation pressure corresponding to the film temperature. For all Pb vapor temperatures considered, the characteristic time is quite small (<0.04 s) compared to the time between shots (0.1 – 1 s) showing that condensation is fast and would probably be more limited by vapor transport to the wall and by the effectiveness of heat transfer from the wetted wall to the coolant. However, the vapor pressure prior to each shot will be higher than the film saturation pressure by up to a factor of ~ 10 . Similar results were obtained for flibe.

III.2 Aerosol Formation and Behavior

Source terms for aerosol formation include ablation of the film due to the initial high energy deposition and formation of aerosol due to in-flight condensation in saturated regions. The large fraction of the indirect-drive target yield carried by X-rays would reach the wall in ~ 10 ns. The spatial profile of this energy deposition would result in part of the wetted wall being vaporized (where the energy deposited exceeds the sensible heat + the latent heat of vaporization) but also with a 2-phase region (where the energy deposited is lower than the above case but still exceeds the sensible heat). It is not clear to what extent this 2-phase region will ablate or stay on the surface. An illustration of this 2-phase region is shown in Fig. 3 for Pb assuming the pressure of the ablated Pb at the interface is 1000 torr.

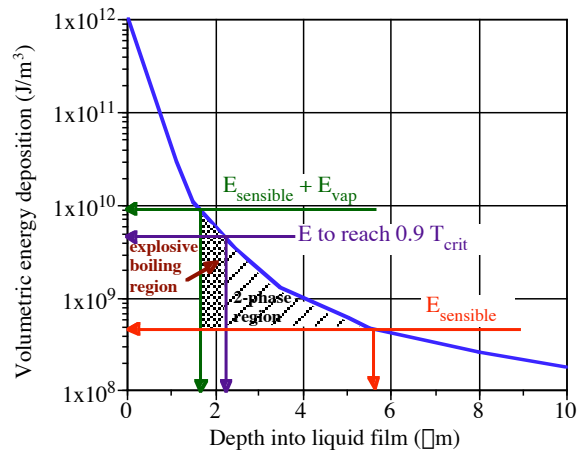


Figure 3 Volumetric heat deposition in a Pb film from 458 MJ indirect-drive photon spectra illustrating 2-phase region and regions where explosive boiling is likely to occur.

The photon energy deposition would occur over a very short time (sub-ns) giving rise to very high heating rates where, in analogy with laser ablation studies[11], the boiling mechanism would be dominated by explosive boiling instead of free surface vaporization or heterogeneous nuclei formation. The process involves rapid superheating to a metastable liquid state which has an excess free energy and decomposes explosively into liquid and vapor phases. Ref. [11] indicates that under these conditions as the temperature approaches 90% of the critical temperature and avalanche-like explosive growth in homogeneous nucleation rate (by 20-30 orders of magnitude) lead to this explosive boiling. This is illustrated also in Fig. 3 as the explosive boiling region. From this figure, two bounding estimate of ablated material can be used as source term for aerosol calculations: (1) an upper bound assuming all material in the 2-phase region is ablated (~ 5.5 μm for Pb and ~ 12.2 μm for flibe); and (2) a lower bound case assuming all material undergoing explosive boiling is ablated (~ 2.5 μm for Pb and ~ 5.5 μm for flibe).

The initial state parameters are supplied to a model [12] that calculates aerosol formation rates and transport behavior. The model calculates vapor saturation ratios throughout the chamber. At locations with sufficient supersaturation, aerosol particles may condense by homogeneous nucleation. Once formed, the particles grow by vapor deposition and agglomeration, and they experience convection due to the velocity of the remaining chamber vapor. The model also calculates vapor mass lost to recondensation onto the wall.

Results of the aerosol calculations at the center region of a chamber of radius 6.5 m are summarized in Figure 4 for flibe under the explosive boiling assumption (2). Heating from ions (~6% of the yield) that arrive later in time were not considered in this analysis. Similar calculations were made for Pb. Given these conditions, ~0.02 kg of flibe aerosol form in the chamber within about 1 ms and ~2 kg in the case of Pb. The figure show the aerosol particle size distribution in the inner chamber region at various time. From these results after about 0.25 s (~the time between each IFE shot), there are still about 10^7 - 10^9 aerosol droplets/m³ with sizes of about 0.3-3 μm for flibe (and about 0.05 –5 μm for Pb) dispersed throughout the chamber volume.

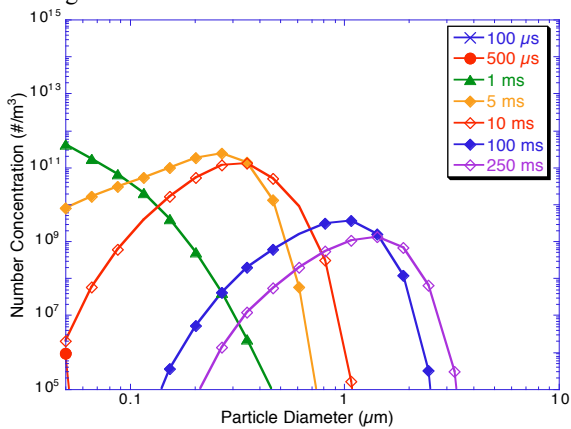


Figure 4 Example of time-evolution of flibe aerosol characteristics in the center of the chamber following a shot for a chamber radius of 6.5 m (from explosive boiling input).

These calculations tend to be conservative as they do not include any processes enhancing chamber clearing. In addition, they do not include the effect of radiation from the vapor which can be important. As the vapor is ejected from the wetted wall under the intense energy deposition, it is driven to the center of the chamber where under compression its temperature increases, which can result in appreciable radiation heat transfer. The vapor pressure and temperature then decrease as the vapor is pushed back towards the wall. This cycle is repeated a number of times until the vapor energy is dissipated (or until the next shot). It should also be noted that these results apply for a 6.5 m wetted wall chamber which is the focus of this paper. It is anticipated that the remaining aerosol mass would be lower for a chamber with finite liquid jets much closer to the target explosion (such as for HYLIFE-II) based on the shorter traveling distance for the vapor and aerosol to reach the wall and based on the higher surface

area associated with the finite jets. This is being studied as part of the on-going effort in this area.

III.3 Preliminary Design Window

The acceptable aerosol concentration and vapor pressure prior to each shot are dictated by target and driver requirements. For a direct-drive target, the chamber conditions constraints are quite demanding based on target thermal and injection requirements. However, for the indirect-drive target protected by a “massive” hohlraum, the requirements are much relaxed [1]. For a heavy ion driver, the requirements posed on chamber gas/vapor and aerosol characteristics depend on the mode of transport and focusing [1]. Neutralized ballistic transport set the most stringent limit based on stripping with integrated line gas density equivalent to about 1 mtorr (~ 3.6×10^{19} atoms/m³). Channel transport set the least demanding limits based on scattering with integrated line density equivalent to about 1 torr. Self-pinched transport is somewhere in between setting limits based on self-pinch resulting with integrated line density equivalent to 100 mtorr.

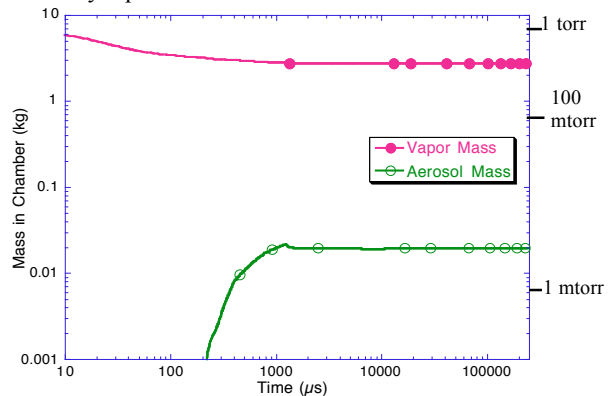


Figure 5 Example of time-evolution of flibe aerosol and vapor mass in the chamber following a shot for a chamber radius of 6.5 m (from explosive boiling input). Also shown is the corresponding average vapor pressure in the chamber.

Results from the aerosol analysis can be used also to evolve an operating design window for a wetted wall concept. For example, Figure 5 shows the vapor and aerosol mass histories for a 6.5 m chamber with a flibe wetted wall exposed to the photon threat spectrum of the indirect-drive target. Clearly, the remaining flibe mass in the chamber is much above the 1 mtorr stripping limit for neutralized ballistic transport. It is also above the self-pinched transport limit of 100 mtorr, leaving only channel transport as a possible mode of ion beam transport. Similar observations can

be made for the Pb case. However, the results must be viewed with caution. On one hand, they are based on the lower bound ablation estimates due to explosive boiling. Similar calculations for the more conservative case where all of the 2-phase region is ablated result in higher vapor and aerosol masses. On the other hand, as explained earlier, the aerosol calculations tend to be conservative in particular since they don't include the effect of vapor radiation. Still, the indications are that aerosol source and behavior are potentially key issues for the wetted wall configuration, which need to be better understood and assessed through future modeling and experimental R&D. Also, the initial estimates of target and driver constraints need to be confirmed through more rigorous derivations.

IV. CONCLUSIONS

Key IFE thin liquid film issues of film re-establishment and coverage and of aerosol formation and behavior have been assessed. Analysis of wetted wall re-establishment and coverage indicates that: (i) liquid film stability may impose a limit on the minimum repetition rate in order to avoid liquid "dripping" into the chamber between shots; and (ii) a minimum injection velocity will be required to prevent the film thickness from decreasing below a minimum value dictated by wall protection requirements. Analysis of thin liquid film forced flow indicates that the normalized detachment distance strongly depends on the Froude number and surface characteristics (i.e. wettability). Efforts in the film dynamics area include generation of generalized charts to help system designers establish parametric design windows.

Analysis of aerosol behavior indicates that significant amount of aerosol could be present prior to each shot. Preliminary estimates of driver constraints on aerosol and vapor mass prior to each shot indicate that the operating design window is marginal. The results indicate that aerosol source and behavior are important issues for the wetted wall configuration, which need to be better understood and assessed through future modeling and experimental R&D. Also, the initial estimates of target and driver constraints need to be confirmed through more rigorous derivations.

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