EVOLVE LITHIUM TRAY THERMAL-HYDRAULIC ANALYSIS

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ABSTRACT

In order to determine whether the EVOLVE fusion blanket design is viable, thermal-hydraulic analyses were performed on the outboard liquid lithium blanket trays. Various methodologies were employed to determine the vapor fraction distribution within these liquid metal trays. Detailed analysis of the vapor fraction is required for understanding of neutron streaming and for heat removal issues involving the liquid lithium trays. The effect of the magnetic field on the liquid lithium pool is still not fully understood and can strongly influence the potential mode of heat removal. Vapor fractions may be greater than 50% for negligible magnetic coupling between the system and the liquid lithium pool. If the magnetic field is coupled to the liquid lithium pool smaller vapor fractions are predicted, ranging up to 12%. Experiments are proposed to determine the magnitude of this coupling and ultimately the vapor fraction distribution of the liquid lithium pool.

I. INTRODUCTION

In order to achieve high power density and high power conversion efficiency in future fusion plants, several first wall and blanket features are required. High power density means the coolant heat removal capability must be significant and high power conversion implies that the first wall and blanket must operate at high temperatures. The first wall material must have high thermal conductivity and low thermal stress, which leads to a high temperature refractory alloy such as tungsten. Because of its limited material strength at high temperature, the operating pressure should be minimized to reduce primary stress and uniform temperatures should be maintained throughout the blanket to reduce thermal stresses. Finally, the large heat of vaporization for lithium makes it ideal as a heat sink for such a blanket.

The EVOLVE[1] (EVaporation Of Lithium and Vapor Extraction) concept was developed to address these specific issues. It uses the vaporization of liquid lithium to remove heat from the fusion system. Trays of liquid lithium are stacked poloidally behind the first wall and receive neutronic heat loads from the plasma. At issue in this study is the localized vapor fraction distribution produced in the trays. This vapor fraction determines neutronic loading on the tungsten trays and the surrounding wall. Three potential flow regimes were envisioned depending on the magnitude of the magnetic coupling to the liquid lithium pool and analyses were developed.

First, a generalized methodology is proposed for determination of the vapor fraction profile for situations of limited or negligible magnetic field interaction with the liquid lithium pool. This methodology uses an empirically derived formulation based on isothermal experiments conducted at the University of Wisconsin.[2] A standard drift-flux model was used to empirically fit data from liquid metal experiments utilizing nitrogen gas as the vapor. We apply this model to the liquid lithium trays. Neglecting magnetic field effects on the liquid lithium trays, predictions indicate large vapor fractions extending up to 65% at the top of the pool.

A second methodology, proposed by Malang (FzK), is utilized to determine the vapor fraction when magnetic field effects are moderately coupled to the liquid lithium.[3] We define moderate magnetic interaction as one where the magnetic field influences the liquid lithium by inhibiting its motion, but does not significantly affect the nucleate boiling process. Mass, momentum and energy balances are performed to validate a potential heat removal scenario where vapor channels are held open by vapor momentum, friction and magnetic field effects. Vapor fraction distributions in this situation for the pool are significantly reduced with values in the range of 6-12%.

Finally, large magnetic field effects are reviewed and potential experiments to resolve the magnitude of the magnetic force on the liquid lithium pool are proposed. There exists the possibility that the nucleate boiling process may be severely inhibited. In this situation the pool depth would have to be sized to maintain the lithium temperature below the tungsten structural limit. We are currently analyzing an EVOLVE system design that operates nominally at 1200 ^oC and 0.037 MPa (saturation conditions), with a surface heat flux of 2 MW/m^2 and a neutron wall loading of 10 MW/m^2.

II. VAPOR FRACTION DISTRIBUTION WITH NEGLIGIBLE MAGNETIC EFFECT ON THE LITHIUM POOL

In a situation where the magnetic effect on the lithium is minimal or none, it can be expected that the liquid lithium will boil like any other liquid metal. The vapor fractions will affect energy deposition in the liquid lithium from neutron streaming. As a first approximation it is assumed that the neutron deposition or heating is directly proportional to the fluid density or inversely proportional to the vapor fraction. A drift-flux model was used with empirically based data from liquid metal experiments with nitrogen gas injection.

A two-dimensional calculation was performed on the nominal design of a tungsten tray filled with liquid lithium. The tray is 50 cm long with a nominal lithium pool depth of 15 cm. The depth of liquid lithium was divided into five axial regions for analysis (3 cm each), with the lateral nodalization characterized by the boiling length scale (equation 1) given by the Taylor bubble size,

$$\text{width} = 2\pi\,[3\sigma/(g\Delta\rho)]^{1/2}. \quad (1)$$

Based on the above approximation, 8–10 cm is the lateral 'cell size'. Based on a 50 cm tray width, the problem was broken down into a 5 (3 cm) X 5 (10 cm) nodal estimation, with the length-wise nodalization dividing the tray into 5 cells. A uniform void distribution of 17%[3] was initially chosen to estimate the neutronic loading (heat deposition).

All the energy deposited in the liquid lithium and in the tungsten tray at the bottom of the cell would vaporize the saturated lithium pool. For each axial region within an individual cell, the quantity of lithium vaporized is then used to determine the volumetric vapor flux (j_g) and the dimensionless superficial gas velocity (J_g), used in the drift-flux model, for bubbly or churn-turbulent flow regimes.[2] Provided below are equations (2) through (7) relating the drift-flux formulation of vapor fraction or void

$$\langle void\rangle = J_g/[C_o\langle J_g\rangle + C_1] \quad (2)$$

$$J_g = j_g/[\sigma_f \Delta\rho g/\rho_f^{\,2}]^{1/4} \quad (3)$$

$$Z = \mu_f/[\rho_f(\sigma_f/(\Delta\rho g))^{1/2}\sigma_f]^{1/2} \quad (4)$$

$$j_g = m_g/(\rho_g A) \quad (5)$$

$$C_o = f_1(H,Z) \quad (6)$$

$$C_1 = f_2(H,Z). \quad (7)$$

The constants C_o and C_1 were experimentally determined from prior tests with mercury, woods metal, water, Freon, dodecane and silicone oils. Nitrogen gas was bubbled up through the pool and the vapor fraction was determined. In the drift-flux model the vapor fractions are driven by the low vapor density of lithium at saturation conditions of 1200 ^oC, and by the nuclear heating loads applied to the tungsten and lithium. Figure 1 shows the relationship of vapor fraction versus superficial gas velocity.

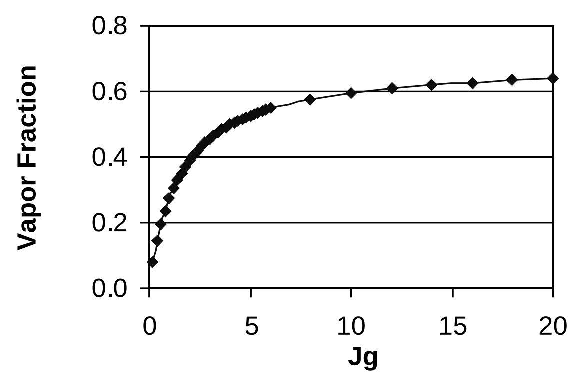

Figure 1. Vapor fraction versus superficial gas velocity for lithium at 1200 ^oC and 0.037 MPa.

Because of the low vapor density of lithium at the nominal conditions large superficial gas velocities are seen for this boiling scenario. This means that generally we see vapor fractions in the range of 60% for the boiling of lithium. The superficial gas velocity scales directly with the nuclear heating, but at sufficiently high values of superficial gas velocity (~ 5) changes in nuclear heating will minimally affect the vapor fraction.

The calculations are iterated with the two-dimensional neutronics calculations as follows. The assumed initial void fraction was 17%, which gives us heating loads that are applied to the drift-flux model. New vapor fraction values are obtained and used to define densities in the neutronics calculation.[4] New nuclear heating values were determined based on the calculated vapor fractions and the iteration process continued until convergence is reached on the vapor fraction. Figure 2 shows the final iterated vapor fraction values at various vertical positions in the pool for the five cells.

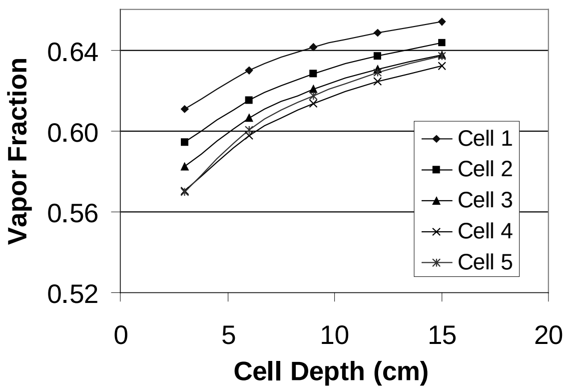

Figure 2. Final cell vapor fractions.

Large vapor fractions were predicted using the Casas and Corradini drift-flux correlation. Other analytical expressions were found in the literature to check against. A study of void distribution in a fuel pool, in the event of a liquid metal fast breeder reactor (LMFBR) accident, was examined.[5] This study was concerned with analytical and empirical expressions of vapor distribution in an internally heated boiling pool. Vertical profiles of the vapor fraction in the heated pool were experimentally obtained and favorably compared to proposed analytical models. An analytical expression for bubbly flow was proposed (equation 8):

$$\alpha = 1-\exp[-GY/(\lambda\rho_v BV_{inf})]. \quad (8)$$

The paper also proposed a classic drift-flux expression (equation 9) to predict macroscopic pool vapor fraction behavior:

$$\alpha = 1-1/[1+2GY/(\lambda\rho_v V_{inf})]^{1/2}. \quad (9)$$

Both analytical expressions use average heat generation rates for the entire pool. Figure 3 shows a comparison of the Casas and Corradini drift-flux void distribution using the central channel, with the two analytical expressions from Kazimi and Chen.

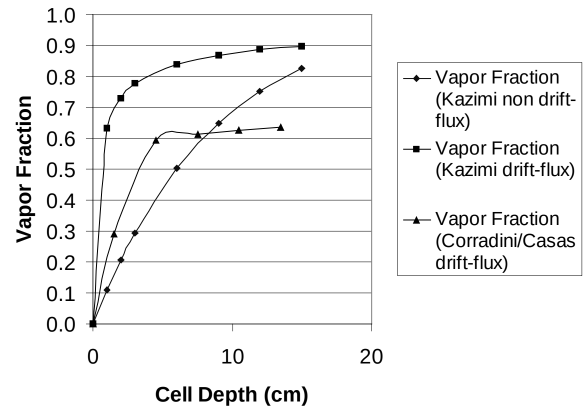

Figure 3. Total pool vapor fraction versus pool depth.

One can see that general agreement exists between the three correlations as to predicting vapor fraction distribution in a boiling pool of liquid lithium with negligible magnetic fluid coupling. It also apparent that the vapor fractions may be very large (> 60%) in this instance.

The vapor fraction appears to be significant but can be reduced by increasing the operating pressure. Figure 4 shows the center channel vapor fraction distribution for various operating pressures using this drift-flux model. It is clear that increases in pressure can significantly reduce pool vapor fractions. Problems arise because of operating limitations on the tungsten metal in the trays. Nevertheless, it is important to understand the effect for potential redesigns and in case of material changes in future designs. Higher operating pressure is advantageous to reducing system vapor fraction.

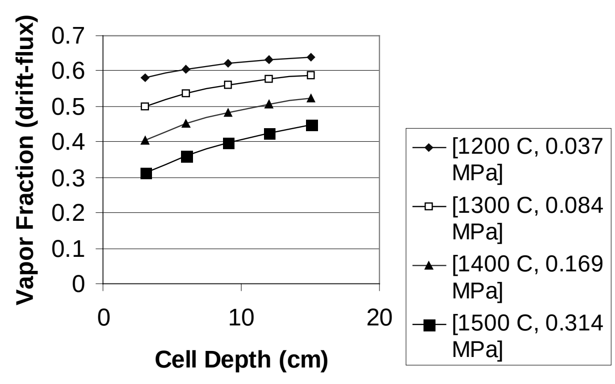

Figure 4. Vapor fraction comparison at different operating saturation conditions.

III. VAPOR FRACTION DISTRIBUTION WITH MODERATE MAGNETIC EFFECT ON THE LITHIUM POOL

Given a moderate magnetic effect an alternative boiling/evaporation picture may emerge with lower vapor fractions. If there is a moderate magnetic interaction with the liquid lithium pool, the magnetic field with vapor momentum and frictional effects may maintain open vapor channels and allow high speed evaporation from the channel interface with less aggregate pool vapor fraction. We define moderate magnetic interaction as one where the magnetic field influences the liquid lithium by damping its bulk motion but does not affect the nucleate boiling process. By providing artificial nucleation sites, we trigger the location of the vapor channels on the bottom of the lithium trays and space them as needed for heat removal. The potential for smaller vapor fractions will exist with the stable vapor channels. Figure 5 provides a schematic of the vapor channels along with a definition of channel and cell size.

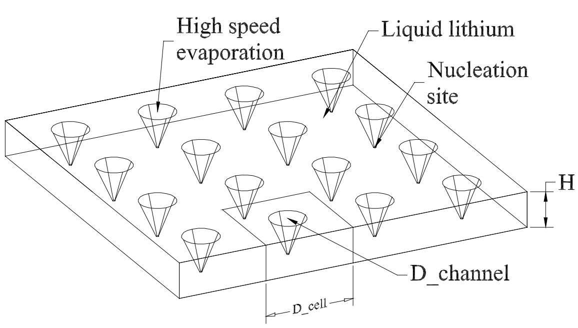

Figure 5. Schematic of vapor channels.

Conduction heat transfer analysis and liquid superheat determine the maximum cell spacing. Past liquid metal boiling data indicate superheats as large as 200 ^oC which would correspond to a maximum cell size of approximately 8 cm. Now a complete analysis combining mass, momentum (pressure) and energy balances will determine the appropriate vapor distribution and spacing to maintain channel integrity and remove sufficient nuclear heat loads. Parameters held constant throughout the analysis were heat generation rate (20 W/cm^3), channel height (15 cm), applied magnetic field (10 tesla) and electrical conductivity (3 X 10^6 A/Vm). Using final iterated heat loading values, from section II, a conservative average was utilized to produce the heat generation rate of 20 W/cm^3.

The iterative process starts with a specific cell size. A guess is then made as to the vapor exit velocity from the channel. Based on that guess an energy balance is performed equating the energy deposited in the cell and the flux of lithium vaporized and exiting the channel. Again, all energy is used to vaporize the saturated liquid lithium. From this the channel exit diameter is determined. Directly from the channel diameter the vapor fraction is geometrically determined and using mass continuity the vapor velocity from the interface of the channel can be found. This leads directly to the liquid lithium velocity that is feeding the liquid/vapor interface. This liquid velocity is important because the movement of the liquid lithium provides the magnetic retarding force (J X B) for the liquid. This is included in the pressure balance that determines whether the vapor channel is stable. The static head of the liquid lithium must be balanced against the kinetic, friction and magnetic pressure head loss terms defined below. Equations (10) through (13) provide specifics about the various terms.

$$\Delta P(\text{static}) = \rho_{liq} g H = \Delta P(\text{fric}) + \Delta P(\text{kin}) + \Delta P(\text{mag}) \quad (10)$$

$$\Delta P(\text{friction}) = (0.03)\rho_{vap}(H/D)v^2 \quad (11)$$

$$\Delta P(\text{kinetic}) = \rho_{vap}v^2/2 \quad (12)$$

$$\Delta P(\text{magnetic}) = \sigma v_{liq} B^2 (L/2). \quad (13)$$

If these pressure terms do not balance then the channel will collapse. An iteration, on the channel vapor exit velocity, is performed until a balance is achieved. Parametric analyses were performed for various cell sizes to determine critical operating characteristics (i.e., channel diameter, void fraction and vapor exit velocity). The balances were performed using two potential length scales (L) in the magnetic head term, the vapor channel or cell size. Since there was uncertainty as to which diameter to use (cell or channel), both were considered and plotted. Significant differences are not seen on the cell vapor fraction or channel diameter plots (Figures 6 and 7).

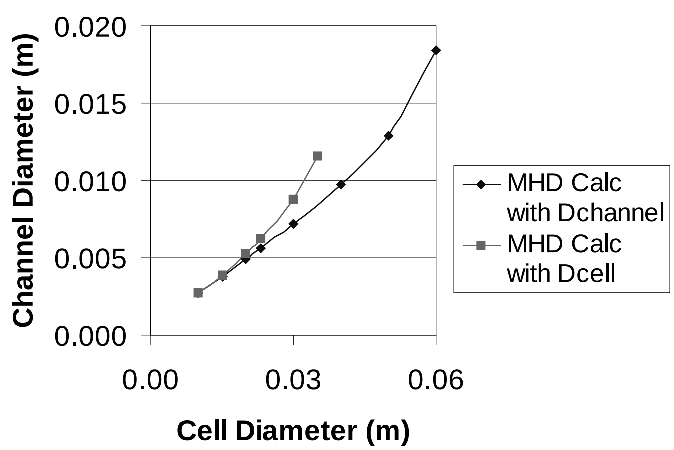

Figure 6. Channel diameter versus cell diameter.

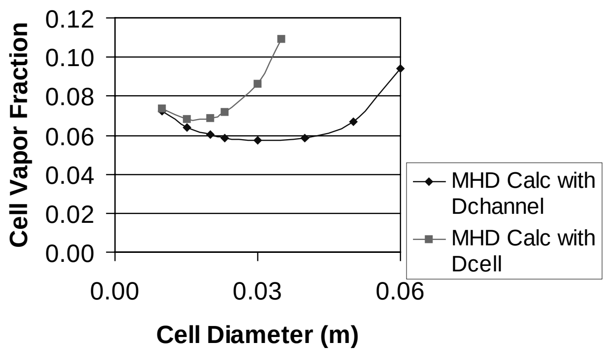

Figure 7. Cell vapor fraction versus cell size.

It is clear from Figure 7 that significantly reduced vapor fractions occur with a moderate magnetic field effect in conjunction with vapor momentum and frictional effects to balance the static liquid head and hold open the channels for vapor outflow.

IV. FUTURE WORK AND EXPERIMENTS

The possibility that the magnetic field may produce a significant interaction with the liquid lithium pool boiling must be addressed. A study of mercury pools, in magnetic fields of strengths around 0.45 tesla, showed significant effects on the bubble departure diameter and its departure frequency during boiling.[6] This has a marked impact on the boiling heat transfer process, but does not seem to alter the onset of boiling even at these field strengths. But this must be confirmed by flow visualization experiments at larger magnetic fields. These experiments are also needed to confirm the expected flow regime with moderate magnetic field influences, discussed in section III.

Based on previous work[6] and the current state of knowledge regarding pool boiling of liquid metals in the presence of a magnetic field, experiments are required. A set of experiments is needed to determine the onset of nucleate boiling and to quantify the effect of various magnetic field strengths on the boiling process; i.e., its onset and bubble dynamics. Once boiling is achieved with the liquid metal in the presence of a magnetic field, real-time visualization experiments of the developing flow patterns would be of great help in confirming the expected flow regime. Then a physical model explaining the effects of the magnetic field on the onset of boiling and the boiling flow regime can be developed. These experiments will allow us to determine the boiling rate and heat transfer for a given volumetric heat flux, which in turn will lead to the pool depth needed to balance heat generation and heat removal.

V. CONCLUSIONS

The EVOLVE plant design has developed a solid wall concept that employs a liquid lithium pool with boiling for power production behind the first wall. Analyses were performed to determine the vapor fraction distribution within this pool of boiling liquid lithium subjected to a transverse magnetic field. Values for vapor fraction ranging up to 65%, and as low as 6 to 12% were estimated depending on the effect the magnetic field had on the pool of liquid lithium (small or moderate). Experiments to definitively show the effect the magnetic field has on liquid lithium have been proposed. These experiments are crucial in the development of the EVOLVE plant design concept in order to confirm the expected flow regime and verify its feasibility.

ACKNOWLEDGMENT

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