Measurements of Vapor Flow Regimes in Liquid Metal Pools

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Abstract:

There is significant ongoing research within the APEX project to develop innovative first wall/blanket concepts capable of efficiently extracting useful thermal energy from magnetic fusion devices that can substantially improve the attractiveness of fusion energy systems. Among the several different ideas are solid and liquid wall concepts. One solid wall concept being considered is the EVOLVE concept. This concept relies on liquid lithium filled tungsten trays to act as a heat transfer and tritium breeding media. In this design liquid lithium flows into tungsten trays and is brought to the saturation temperature by volumetric neutronic heating of the liquid lithium and tungsten trays. The lithium vapor generated could then be used as the heat transfer media for the thermal power cycle. Key to this design is the vaporization and boiling of the lithium in the presence of a strong magnetic fields (~7T). Initial analysis of the boiling phenomena lead to many questions regarding the void fractions and boiling flow regime (void distribution) that may exist in the trays (Anderson et. al. [1]). Since it is necessary to know the void fraction and flow regime present during the boiling process to determine the neutronic heating and energy removal capability, experiments have been initiated to examine this issue. This paper presents initial experiments and scaling analysis for conducted for a new test section which provides real time x-ray determination of flow regimes and void fractions within a pool of low-density liquid metal (NaK) during gas injection inside a horizontal magnetic field. Data will be presented from a first series of tests with gas injection of volumetric flow rates from 0 to 5 SCFH ($0 < Jg < 0.06$ m/s) with no field.

Keywords:
MHD, liquid metal, flow regimes

1. Introduction:

Efficient heat removal at high temperatures is a key issue for blankets in nuclear fusion applications. The EVOLVE (EVaporation Of Lithium and Vapor Extraction) concept was developed in the APEX project as an advanced concept capable of handling high power densities with high power conversion efficiency (Abdou et al. [2], Wang et al. [3]). It utilizes the extremely high heat of vaporization of lithium (about 10 times higher than water) to remove the entire heat deposited in the first wall (FW) and blanket. Tungsten trays filled with Lithium located behind the first wall volumetrically absorb neutron energy, which causes boiling of the lithium and generation of the high temperature (1200 C) lithium vapor. The lithium vapor then leaves the trays as a result of buoyancy forces and is passed though a heat exchanger to heat helium gas for power conversion in high temperature turbines (Mattas et. al. [4]). This concept of liquid metal evaporative heat transfer has been shown to be able to remove up to 200MW/m^2 in heat pipe applications and seems to be a viable option for a highly efficient fusion reactor heat extraction mechanism. One issue however that complicates this design is the presence of strong magnetic fields (up to ~7T), which are used to confine the plasma to the central portion of the tokamak. These magnetic fields result in a horizontal field within the tungsten trays that varies from about ~6T to ~7T(cite). Although the presence of this magnetic field should not influence the vapor movement once it is outside the pool it may have a significant effect on the conductive liquid lithium by altering the boiling regime and the capability of efficient steady state heat extraction.

Previous work in the boiling of a conductive liquid metal in the presence of magnetic fields have been conducted by a several investigators (Wagner and Lykoudis [5], Takahashi [6], Bertodano [7], Eckert [8]). Of these experimental studies only a few are for pool boiling and of these few none have addressed a system similar to the EVOVLE concept design. Wagner and Lykoudis and later Bertodano have conducted experiments with a horizontal field up to 1T in a pool of mercury and Takahashi has conducted experiments with pool boiling of Hg in a vertical magnetic field up to 6T. These experiments give incite into the physics and have helped to define the scope of work necessary to answer some fundamental questions with regard to the feasibility of the EVOLVE concept. Unfortunately the use of a fluid (Hg) with a density 25 times that of liquid lithium and either low field strengths or fields in the wrong orientation along with extremely low superficial gas velocities do not provide a sufficient database to answer the complicated question of what flow boiling regimes may exist in a situation similar to the EVOLVE tray scheme or to compare numerical models.

One important finding of Takahashi 1994 was that there is only a slight (ΔT~10k) change in the onset of nucleation for vertical field strengths up to 6T. This suggests that the presence of the homogeneous magnetic pressure does not substantially affect the temperature at which the conductive fluid would begin to boil. Lykoudis [9] states that in the case of a vertical magnetic field, it is possible that even though the growth of the bubble will be restricted in the horizontal direction, the eventual rising of the bubbles due to the buoyant forces will be along the vertical field lines, thus enhancing the heat transfer to the bulk of the fluid. On the contrary when a horizontal magnetic field is applied, buoyancy will be restrained, and more bubbles will remain longer in their nucleation sites, with the possibility of more direct transition from nucleate to film boiling. Wagner and Lykoudis 1981 saw this in an experiment with fields as low as 1.26T when the temperature of a heating plate rose to 200C above that when the field was not applied indicating the promotion to film boiling that would lead to burnout (figure 1a). Bertodano noticed a similar boiling transition by examining the departure frequency with magnetic field strength for a constant wall heat flux shown in figure 1b. Initially the bubble departure frequency increased as the magnetic field increased, however at a field strength of about 0.7 T a maximum occurred and the field as increased further (up to 1T) a sharp decrease in the bubble departure frequency was observed. Review of these papers leaves several open questions with regard to the EVOLVE concept. First does the magnetic field play a significant role in the characteristics of the boiling regime and if so what are these effects and how do they scale with vapor production. Second, what happens to the heat transfer at strong horizontal magnetic fields and will a vapor layer form on the tungsten tray that could lead to burnout. Lastly, is it possible to obtain high-speed evaporation from channels initiated by artificially creating a nucleation site and how will an applied horizontal field affect these channels. From the results of the previous investigations that the onset of nucleation is not effected significantly by an applied magnetic field, it was determined that we could obtain some answers to these and other questions by simulating boiling with the injection of gas into a low density conductive fluid and directly measuring the void distribution with an X-ray diagnostic. In order to simulate the EVOVLE concept high vapor volumetric flow rates need to be studied with and without an applied magnetic field. This paper will discuss the details of the experimental apparatus and give preliminary data on experiments conducted with no magnetic field. Future work will be conducted to study the effect of an applied horizontal magnetic field.

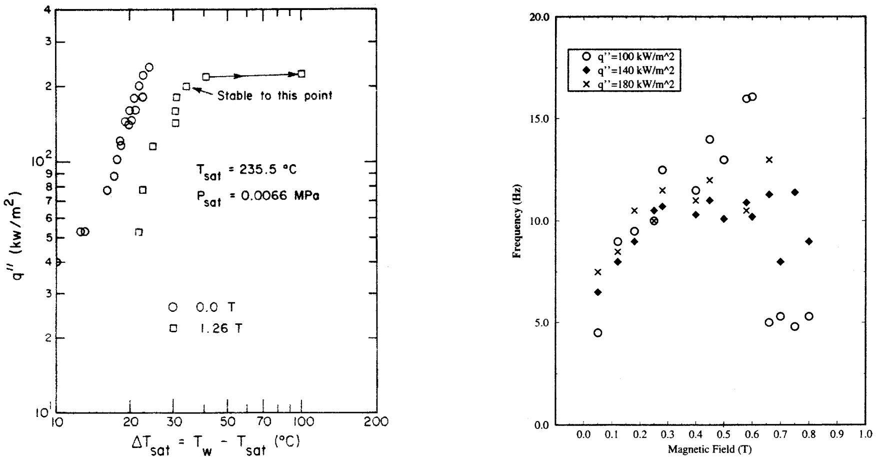

Figure 1. a) Indication of the premature onset of critical heat flux with a horizontal magnetic field of 1.26T applied to a stagnant pool of Hg (Reproduced from Wagner and Lykoudis [9]). b) Bubble departure frequency as a function of horizontal magnetic field strength in a stagnant pool of Hg (Reproduced from Bertodano et. al. [7])

2. Experimental Design:

2.1 Scaling analysis:

A two phase flow regime is dependent on several physical parameters some of these may be incorporated into dimensionless numbers such as the dimensionless superficial velocity (J_g^*), the density ratio of the two mixtures $(r_v/r)_l$, and the Reynolds number of the flow (Re). However due to the complexity of the flow situation and the unknown effect of the applied field it is useful to have as little of distortion in the physical parameters as possible. Since it was not possible to construct a small scale experiment with boiling lithium within the bore of a LHe cooled superconducting magnet it was decided to simulate the liquid lithium with a low density conductive liquid metal NaK (melting temperature –12C) and to simulate lithium vapor production with injected helium gas. Table 1 gives the relevant physical properties of the actual fluids compared to the simulants. As can be seen most of the properties are fairly consistent and the density ratios of the liquid to vapor are equal. The remaining import variable obtaining a similar two-phase flow regime is to have a consistent dimensionless superficial velocity. To estimate this for the EVOVLE boiling scheme we can assume a volumetric neutron energy density of 20W/cm^2 calculated as an average value within a the central portion of an EVOLVE lithium tray with a 55% void fraction (Sawan [10].) Assuming a scaled version of the tungsten tray with a cell volume of 2.54 cm^3 the volumetric flow rate of vapor produced would be 550 cm^3/s, which corresponds to a dimensionless superficial velocity

$$J_g^* = \frac{J_g}{\left(\frac{s_l g(r_l - r_g)}{r_l^2}\right)^{0.25}} \sim 5$$

Properties of Li @ T=1500 K, P= .033MPa	Properties of NaK @ T=293 K, P=0.023 Mpa
μ = 0.0001785 [Ns/m^2]	μ=0.000522 [Ns/m^2]
ρ = 420.1 [kg/m^3]	ρ=860 [kg/m^3]
K = 69.31 [W/m/K]	k=99.2 [W/mK]
σ = 0.1775 [N/m]	σ=0.122 [N/m]
ρ_v = 0.01871 [kg/m^3]	ρ_{He}=0.03829 [kg/m^3]
ρ_e=35.7 μΩ cm	ρ_e=33.5 μΩ cm

Table 1. Properties of Lithium in the EVOLVE conditions and properties of NaK in the experiment. He gas injection can produce a consistent vapor production and a consistent density ratio as compared to the boiling of lithium. Several other key physical properties that may influence flow regimes are also similar.

2.2 Experimental test section:

Figure 2 shows a picture of the test section and its components. The test section has internal dimensions 2.54 cm x 7.62 cm by 5.08 cm which will allow a liquid NaK level of 2.45cm with a 2.54 high gas space above. The bottom plate of the test section has three 1.5mm holes separated by 2.54cm in creating 3 cells of cross sectional area 2.54 x 2.54 cm. Gas can be injected independently in any combination of the injection sites. On the top of the test section is a quartz window for visualization of the top surface, a 6.35 cm diameter gas exhaust port and a port to monitor the test section pressure. The sides of the test section are 0.3125cm thick aluminum, which allow minimal amount x-ray absorption while maintaining structural integrity. The entire test section was designed to fit inside of a 15.24cm boar tube of a LHe cryostat that houses a model A6080-3 American Superconductor solenoid magnet. This magnet and cryostat system allows a fairly uniform horizontal magnetic field up to 6T to be generated through the test section. Figure 2b shows a schematicof the system.

2.3 Diagnostics:

The major diagnostic tool used to quantify the void distribution created by the gas injection was an X-ray absorption technique. This system uses a medical X-ray generator to create 70KeV photons, which will

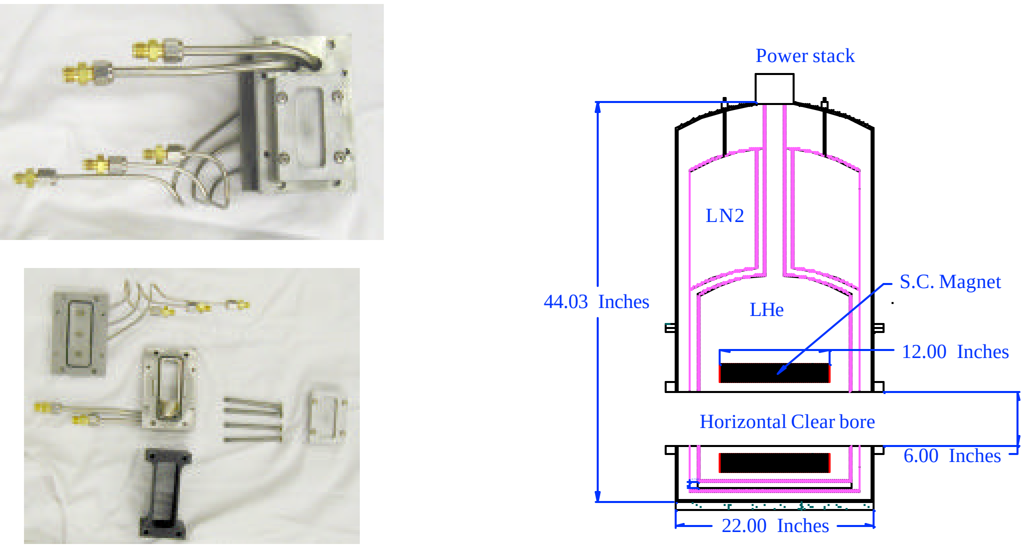

Figure 2: a) Shows a picture of the experimental test section. The three tubes entering the bottom of the test section are used to independently inject gas in to the NaK pool. The two exit ports are for pressure measurement and gas exhaust. The lower portion of a) shows the individual components of the test section. The individual injection sites are seen in the bottom plate. b) Shows a schematic of the cryostat and the magnet system. The entire test section will be inserted into the boar of the magnet/cryostat system during MHD experiments

pass through the test section and contact a scintillation screen. The scintillation screen is then imaged with an intensified CCD camera and the gray level on a pixel is proportional to the number of photons light photons that contact the sensor. The details are presented in (Baker et al. [11]). By creating a calibration that relates a known void to a particular gray level it is possible to obtain the void distribution within the pool during gas injection. To create a calibration file a second test section (calibration section) was constructed that would result in different thicknesses of the NaK. Figure 3a shows a picture of the calibration test section. This was constructed with the same wall thickness as the test section and small hollow tubes were used to create void regions.Figure 3b shows the X-ray image of the calibration section. If one plots the different known voids against the natural log of a non-dimensional pixel value it is possible to obtain an expression for the void.

$$Z_{void} = C_1 \ln\left(\frac{P(x,y) - D}{P_{dark} - D}\right) + C_2$$

where C_1 and C_2 are determined empirically from the graph shown in Figure 3c. From the two dimensional image and the thickness of the void measured with the X-ray absorption on can obtain a pseudo 3-D representation of the void.

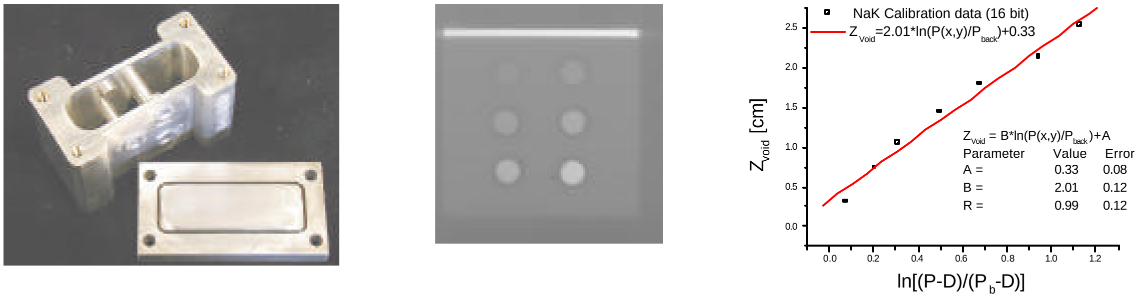

Figure 3: a) Calibration section used to generate known void. b) X-ray image of the calibration block filled with NaK the brightness corresponds to the void thickness. The white line on the top is zero NaK thickness c) Calibration file used to obtain void in cm from the value of the pixels on the CCD array the dots indicate the artificial void in 4b.

3.0 Experimental Results:

Preliminary experiments have been conducted with gas injection into the liquid NaK with no field present to determine the flow regime associated with the gas injection with a similar volumetric flow rate as would be present in the EVOLVE case. Experiments presented here only include a single injection point. Images can be taken at a frame rates up to 200 frames/sec, which allows for real time imaging of the void distribution within the test section. Moderate volumetric gas injection rates of 42cm^3/s result in a bubble departure frequency of 21.4 Hz. At this flow rate the injection seems to be somewhat calm and individual bubbles can be seen in the high-speed images. The constant continuous injection of gas results in a bubble formation at the nucleation site. The bubble remains attached to the bottom surface until the buoyancy force overcomes the surface tension force and then the bubble rises. When the bubble breaks the surface of the pool there is little disruption and little liquid metal carry over. As the flow rate is increased to approximately double (85cm^3/s) the bubbles start to flow into each other and there no longer appears to be a single bubble, rather a continuous stream. At this and higher flow rates the NaK pool is quite violent and there is a significant amount carry over (liquid NaK is ejected from the surface of the pool and entrained into the gas flow). It is anticipated that this violent motion will be substantially reduced in the presence of a magnetic field. Figure 4 shows a single snap shot of the gas injection into the NaK pool at the two different flow rates discussed above. An average void distribution can be determined by averaging the void over all of the 500 frames captured. Figure 5a shows the average void distribution in the pool with a flow rate of 42cm^3/s. As can be seen the average distribution seems to indicate the presence of conical channel within the NaK pool. Figure 5b shows the average line void as a function of position for several different flow rates. As the flow rate increases the average void in the pool increase as evident by the area under the curve up to the kink. The kink in the curve indicates the transition between liquid and gas as the injection rate is increased and liquid is ejected by the bubble leaving the surface of the pool the liquid/gas interface is not as distinct. The sharp dip in the curve indicating a decrease in the line average void within the gas space at approximately 2.5 cm is due to the formation of a bubble of gas at the surface of the pool with a significant amount of liquid over it, which may be due to the formation of an oxide layer on the surface of the pool.

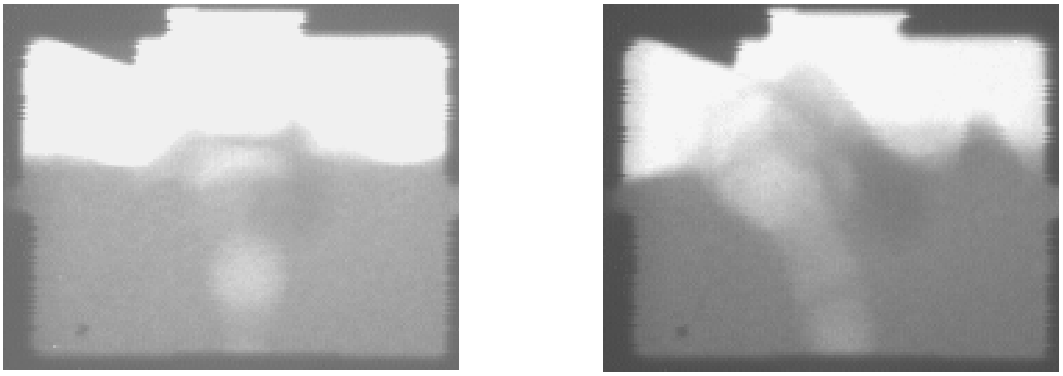

Figure 4 a) Single frame image of the injection of helium into NaK at a flow rate of 42.3 cm^3/s. Images were taken at a frequency of 136 fps. The individual bubbles can be seen. b) Single frame image of the injection of helium into NaK at a flow rate of 85.7 cm^3/s. The higher flow rate causes a violent motion within the pool.

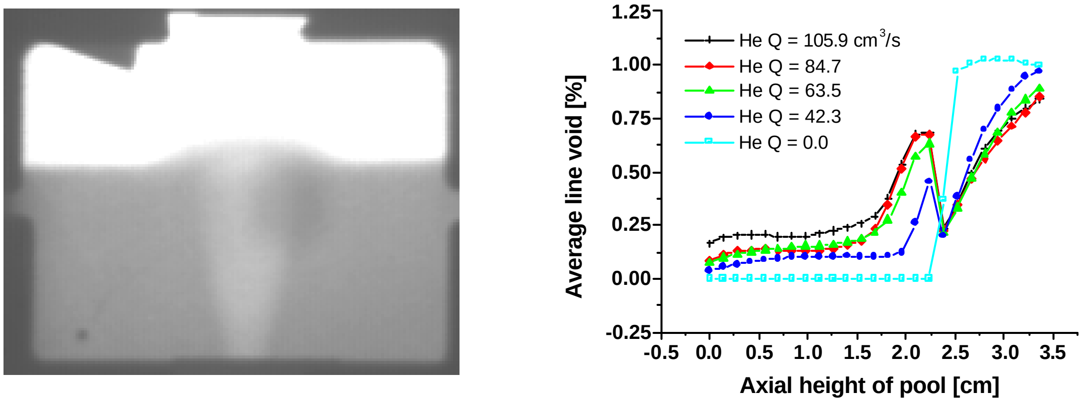

Figure 5. a) Average void distribution in the NaK pool at a flow rate of 42.3 cm^3/s. The level of gray indicates the thickness in to the page of the void. b) Average line void as a function of position for helium injection at several flow rates through the central nozzle.

4.0 Discussion

An experimental system to measure the effects of a strong horizontal magnetic field during gas injection into a pool of molten NaK has been designed to study the void distribution anticipated in the EVOLVE boiling lithium high power heat extraction design. Gas injection was used to simulate the vapor production during boiling and several different volumetric gas injection rates were considered. In this series of experiments without a magnetic field we reached about a forth of the vapor flow rate which would be expected in a scaled version of the EVOLVE concept. At these flow rates significant agitation to the NaK pool was observed along with a significant amount of liquid through to the top of the test section as the bubble left the surface of the pool. This facility will allow future experiments to compare the void distribution present in the pool with no magnetic field with experimental measurements during the application of high (6T) horizontal magnetic fields. The effects of the field on the bubble departure rate and the formation of a vapor layer at the bottom of the pool will be investigated and the feasibility of using the high power density heat transfer mechanism of a boiling liquid metal within a magnetic confinement fusion reactor will be evaluated.

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