FLOW CONTROL AND ASSOCIATED TECHNOLOGIES TO ADVANCE THE APPLICATION OF TEMHD-DRIVEN LIQUID LITHIUM IN FUSION DEVICES

BY

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THESIS

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ABSTRACT

As the fusion research community trends toward building larger and hotter devices, evidence points to the fact that solid plasma facing components will not be able to endure the conditions without extensive damage. Plasma-materials interactions with these surfaces lead to material defects, impurity formation, and cooling of the edge plasma. In order to alleviate these serious issues, liquid metal concepts are being heavily researched as alternative plasma facing components. Liquid lithium has shown the most promise, as its use in fusion devices has led to increased confinement time, less wall recycling and improved impurity control, and enhanced plasma performance. Many early devices used lithium evaporation or pool melting to introduce lithium, but the high reactivity of liquid lithium quickly led to passivation of the surface.

To mend this problem, flowing liquid lithium systems have been developed that provide a constantly refreshing liquid lithium surface to the regions of plasma interaction. The Liquid Metal Infused Trench (LiMIT) concept, developed at the University of Illinois at Urbana-Champaign (UIUC), utilizes the thermoelectric magnetohydrodynamic (TEMHD) effect to passively drive liquid lithium through solid metal trenches. The LiMIT device has been successfully tested at UIUC and in devices around the world, such as the HT-7 tokamak and the Magnum PSI linear plasma device, at heat fluxes of up to 3 MW/m². While sustained flow has been observed in many cases both horizontally and at an arbitrary angle to horizontal, methods to control and constrain the flow are lacking.

This thesis focuses on modeling and experimental techniques meant to aid in lithium flow control in LiMIT devices. A compact flow module was developed that utilizes the nozzle effect to drive high-velocity flow when impacted with high local heat fluxes. The proof of concept testing showed sustained flow between 2 and 10 cm/s in the device, and associated modeling predicts velocities up to 60 cm/s will be attainable once used with large heat fluxes. The dryout phenomenon, where high local acceleration of flow depresses lithium surfaces and exposes the solid trenches, is investigated via multiphysics modeling. The models developed recreate experimental observations, and were used to predict that a step increase of the height of the bottom of the LiMIT trenches can effectively mitigate dryout risk in future devices. For flow of 1 cm/s in a 5 mm deep trench, a step increase of 1.8 mm is most effective, while for 10 cm/s
flow, a step increase of 2.7 to 3.0 mm works to diminish dryout. Finally, a method to control the wetting properties of liquid lithium on stainless steel and molybdenum is developed. Pulsed laser interaction with the metal surfaces creates relatively ordered micro and nanostructures that serve to increase the wetting temperature of lithium. On stainless steel, this increase is 83 °C (to 398±4 °C), and on molybdenum, it is 77 °C (to 401±4 °C). Furthermore, it is shown that the change in wetting temperature increase can be used to accurately predict the surface roughness of the structured materials, or that experimental observations of a structured surface can be used to predict the wetting temperature.

Overall, the models and technologies presented herein describe various methods of controlling and constraining lithium in a flowing liquid lithium device. The information can be used on future iterations of LiMIT testing on larger devices, like the design for a LiMIT limiter for the Experimental Advanced Superconducting Tokamak (EAST) presented in this work. As flowing liquid lithium concepts continue to be developed, the adaptable models and technologies shown here will be used to inform the design process and inform engineering decisions, in order to further the applicability of liquid lithium in large scale fusion devices.
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CHAPTER 1 – INTRODUCTION

1.1 Fusion Power

The successful harnessing of fusion power stands to be one of the greatest achievements in the history of mankind. This zero-emission power source promises low levels of radioactive byproducts, high efficiency, and nearly unlimited fuel in the form of deuterium, found naturally in water. The development of fusion power has progressed for over half a century without creating controlled net power output, to the dismay of many proponents of the technology. However, huge strides have been made in that time in the areas of plasma and nuclear physics, reaching ever closer to this coveted goal.

Likened to trapping the sun on Earth, the challenges associated with fusion power development are plentiful. At the temperatures required to increase the reaction cross section enough to make fusion viable, gases become ionized plasmas. In describing the energy balance in a hot fusion plasma, the Lawson criterion was developed to describe how energy relates to the temperature, density, and confinement time of fuel components. A close corollary became known as the “triple product”, a multiplicative metric that any concept of fusion power production must achieve in order to produce net energy. For self-sustaining deuterium-tritium fusion, the easiest fusion reaction to achieve, this is given by

\[ nT \tau_E \geq 5 \times 10^{21} \text{ keV } s/m^3 \]  

(1.1)

Where \( n \) is the electron density (due to quasi-neutrality in a fusion plasma, \( n = n_e = n_i \)), \( T \) is the plasma temperature, and \( \tau_E \) is the confinement time. Above the value given, the fusion energy released will exceed the power required to heat and confine the fuel. While many methods of creating and containing plasmas have been proposed, the most noteworthy can be grouped into 2 main categories: inertial confinement fusion and magnetic confinement fusion.

Inertial confinement fusion typically utilizes laser beams to impact and quickly condense a small pellet of fuel. The strategy attempts to maximize \( n_e \) while \( \tau_E \) is quite low, on the order of nanoseconds. In the United States, the National Ignition Facility is one of the pioneers of this technique, using 192 beams to compress and blow apart a hohlraum structure that surrounds
fusion fuel. The destruction of the hohlraum creates x-rays meant to create further compression. In many cases, the perfect symmetries required and instabilities of the plasma at very high pressure cause density and confinement time to suffer.

Magnetic confinement fusion has received the overwhelming bulk of focus and funding over the years. It approaches the triple product using lower densities than inertial confinement, but hopes to reach confinement times on the order of seconds. It takes advantage of the fact that plasmas can be controlled by electric and magnetic fields. Ionized particles and electrons tend to stay confined to field lines, orbiting them and travelling along them rather than diffusing across them. Since particles will continue to travel along said field lines indefinitely, the brilliant idea was proposed to loop them back upon themselves. In this way, the magnetic field lines, and therefore the plasma, form a torus, allowing for continuous confinement and heating of the plasma. This led to the toroidal magnetic confinement concept, which includes both stellarators and tokamaks. Tokamaks are the most well-studied and widespread method of developing fusion plasmas, but they do not come without their faults. New drifts and instabilities were discovered in these plasmas due to magnetic field, density, temperature, and pressure gradients, and this led to reduced confinement and lower temperatures\cite{12-5}. As new confinement techniques and better operating modes (such as the H-mode) were discovered\cite{6}, it seemed as though they always brought new problems and instabilities with them. These pressure and current driven instabilities can lead to large disruptions and edge localized modes (ELMs) that cause plasma ejection from the core to deliver a substantial fraction of the total energy to the wall of the device within a fraction of a second.

It is not only disruptions that cause problems at the walls. A tokamak contains plasma many times hotter than the center of the sun, and diffusion and drift result in inevitable plasma-material interaction (PMI) at the wall. Neutrons also carry a majority of the released energy of the fusion reaction, and since they are not affected by the magnetic fields, travel straight to the walls. Wall materials must contend with this high heat load without melting, and furthermore, recycling from the wall can cool the plasma, hindering fusion. If a particle diffuses to the wall and rebounds, it can thermalize and rebound at the temperature of the wall, cooling the edge plasma. Furthermore, if the particle was neutralized at the wall, it can easily diffuse into the
core, causing massive cooling in the hottest parts of the plasma. This recycling is enhanced if the plasma sputters high atomic number (high-Z) particles off of the wall and back into the core.

As tokamak plasmas get larger and hotter, leading to the development of the International Thermonuclear Experimental Reactor (ITER), the world’s largest tokamak\(^7\), material constraints of wall materials have not changed much. In order to protect the bulk of the first wall, plasma facing components (PFCs) known as limiters and divertors have been introduced. These PFCs are built to receive the bulk of the heat loads that stream out of a tokamak plasma along the last closed magnetic flux surface. In these high intensity conditions, even tungsten, the element with the highest melting temperature, sustains heavy damage. Melting and thermal damage arise from the high heat fluxes\(^8-10\), and longer term effects of neutron irradiation damage and fuzz formation from plasma interaction degrade the material\(^11\). When sputtered, high-Z materials like tungsten also heavily contribute to plasma cooling via Bremsstrahlung radiation losses that are proportional to Z\(^2\). When first wall components are all high-Z substances, impurity egress into the core plasma can be quite damaging to the plasma performance. These heat loads are also only expected to increase. Even with flux spreading and plasma shaping techniques meant to minimize heat flux impingement on the divertor, plasmas in ITER are expected to reach over 10 MW/m\(^2\) at the divertor surface\(^12-14\).

1.2 Fusion and Liquid Lithium

Since current cooling systems are struggling to be sufficient for use with solid PFCs, a growing section of the fusion community is studying the benefits of liquid metals in fusion applications. While many of these ideas have existed for some time, the increasingly intense conditions expected in reactor relevant fusion devices has led to a resurgence of study in these areas. The Advanced Limiter-divertor Plasma-facing Systems (ALPS) and Advanced Power Extraction (APEX) initiatives have received extensive funding to develop novel methods of using liquid metal systems as PFCs\(^15-17\).
1.2.1 The Benefits of Lithium

Of the liquid metals under investigation, lithium has found the most support, due to several benefits it provides in fusion systems. Lithium is a low-Z element, the lowest besides hydrogen and helium, meaning if it is sputtered or evaporated into the plasma it will effect minimal losses on core plasma performance. The use of lithium can also be quite beneficial to fusion device operation.

Since the first definitive results of lithium-driven performance increases in TFTR\cite{18}, lithium has been shown to provide low recycling, increased confinement time, increased and more stable density profiles, and even ELM mitigation. Since 2005, the FTU device in Italy has been operating with a lithium limiter, and has experimented with lithium wall conditioning. They saw sudden increases in core density as soon as lithium use began, as well as reliable 20% increases in confinement time\cite{19}. CDX-U at PPPL installed a fully toroidal liquid lithium limiter and observed much lower recycling at the wall, along with fewer oxygen and carbon impurities. $Z_{eff}$ of the core was reduced 50%, and they achieved a 25% increase in core temperature\cite{20,21}. The reduction in recycling tends to reduce the temperature gradients at the edge of the plasma, allowing a larger volume of plasma to stay hot and effective for fusion. The LTX experiment even recently announced a completely flat radial temperature profile, with no reduction in temperature at the edge, due to the effects of lithiated walls\cite{22}. NSTX and NSTX-U at PPPL has also experimented extensively with lithium, developing a liquid lithium divertor and lithium evaporators to cover sections of the wall\cite{23,24}. Increasing coating thickness of lithium on the walls of the device was shown to decrease recycling, improve energy confinement, and reduce the edge density gradient profile\cite{25}. The lithium coating affected edge plasma profiles by lowering the density, pressure, and current gradients, rendering them more stable to the instabilities that lead to ELMs. This led to periods of ELM-free H-mode operation, known as the quiescent H-mode\cite{26}. Confinement was also markedly improved during the periods of quiescent discharges. Another concept utilizing the benefits of lithium is ELM pacing. Instead of allowing instabilities to grow and crest into large, relatively unpredictable ELMs or disruptions that could quench the plasma, pellet injection was found to be able to produce a pseudo-quiescent H-mode where pellets would trigger small ELMs at a regular frequency, essentially releasing tension in the plasma and allowing for more stable operation. DIII-D had proposed this method in
conjunction with fueling by deuterium pellet injection as a mitigation strategy for ITER\cite{27}. Recently, lithium pellet injection was also attempted, successfully triggering ELMs at a higher rate with lower peak heat flux. The lithium also lowered impurity concentrations in the plasma core, and resulted in good H-mode energy confinement and pedestal characteristics\cite{28,29}.

1.2.2 Flowing Liquid Lithium Technologies

As seen above, many devices have examined the effects of incorporating solid or liquid lithium into device operation, to encouraging results. However, lithium also has its drawbacks. It is a highly reactive metal that acts as a strong getter to many common impurities in tokamaks. While this makes its low recycling ability possible, it makes it very difficult to keep lithium pure, both in atmosphere and in vacuum. Lithium also has a large affinity for hydrogen and its isotopes, requiring fueling rates to be largely increased when lithium is present. Many devices have just used open pools or evaporated films of lithium, and the high reactivity of liquid lithium can lead to diminished performance over the course of run campaigns. To this end, researchers have developed ways to utilize flowing liquid lithium in PFCs to maintain clean surfaces and provide continuous enhancement of plasma properties. There are 3 main types of these systems: capillary porous systems\cite{30,31} that intercalate liquid lithium in another porous metal, radiative divertor system\cite{32,33} that take advantage of lithium evaporation to disperse incoming heat flux, and open surface flow systems, that present a free surface of liquid lithium as a PFC\cite{34,35}. This work will focus on these open surface systems.

There are two main concepts for free surface flowing lithium PFCs: the Flowing Liquid Lithium (FLiLi) concept developed at PPPL, and the Liquid-Metal-Infused Trenches (LiMIT) concept developed at UIUC. Flowing liquid lithium surfaces can alleviate the issues solid PFCs face by presenting a constantly refreshing liquid surface that is immune to damage and passivation, reduces erosion of high-Z materials and their entry into the plasma, and improves heat transfer while protecting the solid surfaces beneath.

The FLiLi concept consists of a thin film of lithium that falls down a smooth plate. Lithium is pumped to the top of the device and pushed through a distributor nozzle, a series of small holes meant to disperse the flow into a thin film. The plate is cooled from beneath, allowing the temperature of the lithium to stay in a low evaporation regime. Designs of this
The LiMIT concept seeks to alleviate some of these problems. It consists of an array of solid metal trenches (usually stainless steel though molybdenum and tungsten have been studied) that are filled with liquid lithium. When 2 different metals share an interface and a temperature gradient is applied along that interface, a voltage difference is developed due to the Seebeck effect. As a result, a thermoelectric current begins to circulate around the junction between the 2 metals. In the case of LiMIT, a thermal gradient is created along the height of the trenches, either by coolant passing through the device or by a plasma impinging on the top of the lithium surface. This generates a thermoelectric current that circulates through the liquid lithium. Then, a transverse magnetic field creates a \( j \times B \) Lorentz volume force that can actually passively drive the lithium through the trenches. When trenches continue along the underside of the device, full recirculation of the liquid lithium is possible. This thermoelectric magnetohydrodynamic (TEMHD) driving force is the key to the LiMIT system. This effect is described in more detail in Chapter 2. As a PFC, the LiMIT device can utilize the plasma heat flux and toroidal magnetic field to create self-driven TEMHD flow, without the need for any external pumping. Diagrams of the concept are presented in Figure 1.1.

Figure 1.1 – A diagram of the LiMIT concept showing the trench system and how the necessary components of the TEMHD effect act to drive liquid lithium flow.
This system has been developed and tested extensively at UIUC, where horizontal and vertical flow have been sustained. The high surface tension of liquid lithium helps to constrain it inside the trenches, but still allows flow to occur. This results in smooth, even films of liquid lithium that are constantly refreshing in the face of plasma impingement. The TEMHD circulation aids in heat transfer and reduces the effects of high heat flux divertor heat stripes. The system has been tested in the HT-7 tokamak and the Magnum PSI linear plasma device, performing effectively at fusion relevant conditions up to 3 MW/m². Experiments have also been conducted to test the extent to which the trenches are able to constrain the liquid lithium and deny the ejection of droplets from the surface. Proof of concept tests rotated the system past vertical, so the open surface was facing downward. Up to 180° from horizontal (fully upside down), the lithium surface stayed stable, flow was sustained, and no spilling occurred. Further testing exposed the LiMIT system to ELM-like conditions and determined stability criteria for lithium ejection, showing the trench sizes commonly used are quite stable up to very large plasma impulses.

1.3 Thesis Objectives

While much testing has been done on the LiMIT system, there are several tangential aspects of the technology that must be addressed in order to truly propel this system to feasible use in large scale fusion devices. This work focuses predominantly on topics associated with the flow control of LiMIT systems. In high heat flux applications, controlling and increasing the velocity of liquid lithium flow can aid in heat flux removal and provide enhanced surface replenishment. However, in early tests of the LiMIT device at UIUC, high electron-beam heat fluxes drove local acceleration that led to depression of the liquid lithium levels known as dryout. This phenomenon can expose the solid trenches, allowing the problems mentioned for solid PFCs to persist. Dryout is relatively unique to flowing liquid lithium PFC designs, but must be accurately modeled and alleviated in order for large scale systems to prove viability. Finally, lithium does not always go where desired. Lithium’s high surface tension at times inhibits wicking into trenches, and other times drives rapid wicking onto surfaces outside of the testing device. Therefore, this work builds off of recent results and provides the finishing touch to a series of methods for controlling the wetting properties of liquid lithium on commonly used
LiMIT substrates. These methods can come together to provide a thorough system for better control of liquid lithium flow in large scale applications of LiMIT, and the designs for the development of a LiMIT-based limiter on the EAST tokamak are presented here.

1.4 Thesis Overview

This thesis provides several technologies that can be used to direct more efficient flow control of liquid lithium in PFC concepts. Chapter 2 details the development of a compact, high velocity TEMHD-driven flow concept. The theory and modeling are described, along with the proof-of-concept experimental tests and their validation of the model. Chapter 3 computationally investigates the dryout phenomenon using multiphysics simulations. Results of the model and experimental analogues are presented, along with a model extension that provides insight into dryout mitigation using shaping of the LiMIT trenches. Chapter 4 describes the wetting properties of lithium on micro and nanostructured stainless steel and molybdenum samples. A theoretical look at how wetting temperature and structure characteristics are related is also given. Chapter 5 presents the initial designs for a LiMIT system to be tested as a limiter in the EAST tokamak, along with modeling and calculations supporting design choices. The thesis will then conclude with a summary of the previous chapters and discussion of future work.

Overall, the methods presented here form an effective set of techniques and technologies to harness and control flow in liquid lithium PFC devices, especially those relying on the TEMHD effect. Chapter 2 provides the basis for the ability to regulate lithium velocity at will, while still utilizing the passive pumping of the TEMHD effect. Coupled with Chapter 3, this provides a way to adjust flow conditions and avoid the dryout phenomenon that plagues flowing liquid lithium devices. The wetting tests presented in Chapter 4 show that a surface structuring technique can change how lithium wets solid surfaces, providing further means to dictate lithiated regions and flow behavior. Furthermore, the models developed throughout these chapters provide a way to enhance the design process as it currently exists. As the models are validated by experimental tests and observations, they become valid predictors for flow behavior in future geometries and the performance of future concepts. Designs can be iterated upon virtually, instead of requiring extensive machining and physical testing between each attempt.
Utilizing these techniques, the development of liquid lithium PFCs can progress toward full scale implementation on large, high intensity fusion devices.
CHAPTER 2 – HIGH VELOCITY TEMHD-DRIVEN FLOW

2.1 Background

As was mentioned earlier, liquid metal PFCs are very attractive alternatives to standard solid materials. While solid tiles are static and can be incrementally damaged over time (or suddenly demolished by a large disruption) liquids are self-healing, and a flowing liquid surface constantly provides a refreshing source of new material. LiMIT and other flowing liquid metal technologies have been tested and proposed for use in several large-scale devices, and as the device size increases, so does the expected heat load. Liquid lithium is a good choice for liquid metal PFCs due to the fact that it is low Z and low recycling, but its low melting point and relatively high vapor pressure can become problematic as heat loads increase. In order to mitigate the risk of strong lithium evaporation, flow speeds need to reach upwards of several meters per second for some applications. These applications are predominantly ones where lithium is used as a beam target, like the International Fusion Materials Irradiation Facility in Japan. However, divertor heat stripes in large fusion devices reach very high heat fluxes as well, and as the fusion community continues to work toward feasible power production, these heat loads will continue to increase. Current high heat uses of lithium require strong pumping systems and bulky infrastructure overhead to maintain these flow speeds, limiting the portability and modularity of the system.

This chapter details a new method for developing high velocity TEMHD-driven flow that is based off of the LiMIT concept. The idea utilizes proven physics to create a system that should be able to sustain high velocity liquid lithium flow in a compact, self-contained system. Self-driven TEMHD flow is uniquely suited for this since it has the ability to increase flow speed passively as the heat flux is increased. The flow is then coupled with the nozzle effect for further constraint and higher velocities.

In order to present a comprehensive view of the design process and foster a justification of the design parameters, it is important to show the derivation of TEMHD-driven flow in a LiMIT-like trench system. The derived expressions will show how several potential design/system parameters characterize the flow and inform engineering decisions. The
derivation of TEMHD flow was first worked out by Shercliff in 1979[46], and is modified here in the boundary conditions for trench flow.

The thermoelectric effect is the ultimate basis for TEMHD flow. This is the effect used in thermocouples to measure temperature. Concisely, it says that when 2 dissimilar metals share a junction, and there is a thermal gradient along that junction, there will be a voltage difference between the top and the bottom of the interface. This voltage difference creates an electric current. The voltage difference induced is a result of the Seebeck effect. The Seebeck coefficient, also known as the absolute thermoelectric power or thermopower, is a measure of the thermoelectric voltage that can be induced across a material. A difference in thermopowers between materials is what gives rise to the thermoelectric effect and the thermoelectric current. Ohm’s law must then be adjusted and generalized to account for this generated current.

\[
\frac{j}{\sigma} = E + \bar{u} \times \bar{B} - S \nabla T 
\]

(2.1)

Where \( j \) is the current density, \( \sigma \) is the electrical conductivity, \( E \) is the electric field, \( \bar{u} \) is the velocity, \( \bar{B} \) is the magnetic field, \( S \) is the Seebeck coefficient, and \( \nabla T \) is the temperature gradient. The \( \bar{u} \times \bar{B} \) term is used to describe the electromotive force (emf) from the velocity, and the Seebeck coefficient term is added here to describe the emf from the Seebeck effect. A simple diagram of the thermoelectric effect is given in Figure 2.1.

**Figure 2.1** – A simple diagram of a thermocouple junction, which leads to a thermoelectric current as a result of the temperature difference between the 2 sides of the interface.

It is important to note that for a stationary single material, while a thermoelectric emf is generated, there is no thermoelectric current. It requires the junction of 2 different materials with differing thermopowers and a temperature gradient parallel to the junction to develop a
thermoelectric current. Referring to the thermocouple diagram in Figure 2.1, it is possible to
determine the emf by integrating over a closed loop that encloses the extent of the junction.

\[
\varepsilon = \oint -S\nabla T \cdot d\vec{r} = - \int_{T_1}^{T_2} S_A \nabla T \cdot d\vec{r} + \int_{T_1}^{T_2} S_B \nabla T \cdot d\vec{r}
\]

\[
= \int_{T_1}^{T_2} S_B dT - \int_{T_1}^{T_2} S_A dT = \int_{T_1}^{T_2} P dT
\]  

(2.2)

Where P is the thermoelectric power between the pair of metals. It can be seen that the
emf generated is only dependent on the difference in the temperature at each side of the junction.
If there is a current loop other than the interface, however, this thermoelectric emf would not be
created. As the current develops, the Peltier effect and Thomson effect generate and transfer
extra heat through the system, but these effects need not be examined in detail, as the additional
heat is negligible in relation to the latent heat and external heat fluxes present in the system.

So there exists a closed current loop flowing around a junction between two metals. If
one of the metals is liquefied, the current will still flow from the solid around through the liquid.
This means that if an external magnetic field is applied that has a transverse component, a \( j \times B \)
Lorentz force will be generated, causing the liquid to flow. The concept of thermoelectric
magnetohydrodynamic (TEMHD) flow is born. The MHD equations must be slightly adjusted to
account for the thermoelectric terms. Assuming the liquid metal is incompressible, and that the
magnetic Reynolds number is small so the liquid flow does not interfere with the magnetic field
(this is generally true, including for lithium), the equations can be written as

\[
\nabla \cdot \mathbf{\tilde{u}} = 0
\]

(2.3)

\[
\nabla \cdot \mathbf{j} = 0
\]

(2.4)

\[
\mathbf{j} = \sigma \left( \mathbf{E} + \mathbf{\tilde{u}} \times \mathbf{B} - S\nabla T \right)
\]

(2.5)

\[
\rho \left( \frac{\partial \mathbf{\tilde{u}}}{\partial t} + \mathbf{\tilde{u}} \cdot \nabla \mathbf{\tilde{u}} \right) = -\nabla P + \mu \nabla^2 \mathbf{\tilde{u}} + \mathbf{j} \times \mathbf{B}
\]

(2.6)

\[
\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T)
\]

(2.7)
Here, $\rho$ is the density, $P$ is the pressure, $\mu$ is the dynamic viscosity, $C_p$ is the heat capacity of the liquid, and $k$ is the thermal conductivity. It is now time to calculate the flow conditions, namely velocity, in a trench system like the LiMIT device. LiMIT, as described in the introduction, is comprised of a series of solid stainless steel trenches containing liquid lithium. When the center of the device is cooled, a temperature gradient is formed from heater plates on the underside of the return channels and/or a topside heat flux provided by an e-beam or divertor heat stripe. This, in addition to a transverse electric field, propels lithium through the trenches. The thermoelectric current flows predominantly in the $y$ direction, looping near the top and bottom of the interface, which can be seen in previous computational results displayed in Figure 2.2.

![Figure 2.2](image)

Figure 2.2 – Results from previous computational work on a computational solution for the thermoelectric currents flowing through a LiMIT trench. The background color map represents temperature, while the arrow field displays the thermoelectric current. The magnetic field and the TEMHD force are also labeled.

For the purposes of simplifying the trench system and deriving the average flow velocity in the trench, this system can be approximated as a 1D open surface rectangular duct flow, as seen in Figure 2.3.
Figure 2.3 – Simplification of a LiMIT trench to the case of rectangular duct flow. The walls, shown in gray, are interspersed with lithium, shown in blue. This diagramed system is used to derive the TEMHD flow velocity field.

In this image, the trench domain containing liquid lithium is 2a wide, and the trench walls are t thick. It is important to note that the coordinate system used for this derivation is not the coordinate system used later for COMSOL modeling. The physics remains identical, but extra attention must be paid to the setup and flow direction. The temperature gradient is also in the y direction, while the magnetic field is in x. In this case, the TEMHD effect drives flow in the z direction, and small non-ideal velocities in the x and y directions are neglected for the purpose of this analysis. Ohm’s Law yields the current in the liquid metal

\[ j = \sigma Bu + j_s \]  

(2.8)

Where \( j \) is the total y directed current and \( j_s \) is the value of the current at either wall. This current begets an extra term in the convective-form incompressible Navier-Stokes equation, which becomes

\[ 0 = -\frac{dP}{dz} + \mu \frac{d^2u}{dx^2} - jB = 0 \]  

(2.9)

With \( \frac{dP}{dz} \), a constant pressure gradient term. Substitute Eqn. 2.8 above into Eqn. 2.9 above and rearrange to get
\[
\frac{d^2u}{\mu dx^2} - \sigma B^2 u = \frac{dP}{dz} + j_s B
\]  

(2.10)

Applying a no slip boundary condition at \( \pm a \) and solving the above equation for the velocity results in

\[
u = -\frac{1}{\sigma B^2} \left( B j_s + \frac{dP}{dz} \right) \left[ 1 - \frac{\cosh \left( \frac{H_a x}{a} \right)}{\cosh (H_a)} \right]
\]  

(2.11)

Where the Hartmann number, \( H_a \), is used to simplify some parts of the expression. The Hartmann number is given by

\[
H_a = BL \sqrt{\frac{\sigma}{\mu}}
\]  

(2.12)

With \( L \) meaning the characteristic length of the fluid. In this case, \( L \) is taken as the width of the liquid filled trench or duct. The Hartmann number, defined by Hartmann in 1937\(^{[47]} \), gives the ratio of the electromagnetic force to the viscous force, and the velocity equation given above is the velocity profile generally referred to as Hartmann flow. It is more useful for design to consider the average velocity through the channel, without worrying about the details of the actual shape of the velocity profile. To that end, taking the integral of the profile over the width of the trench yields the average velocity

\[
u_{avg} = -\frac{1}{\sigma B^2} \left( B j_s + \frac{dP}{dz} \right) \left[ 1 - \frac{\tanh (H_a)}{H_a} \right]
\]  

(2.13)

In order to complete the expression for the average velocity, the current must be found. Kirchhoff’s current law dictates that any current flowing into a node must flow out. Extending this to the system in question, it means that the total current flowing in the liquid must equal the total current flowing through the walls. Defining the total current density in the walls as \( j_w \), the equality comes out to

\[
a \left( \sigma B u_{avg} + j_s \right) = -t j_w
\]  

(2.14)
Kirchhoff’s voltage law then says that the sum of all voltages around a loop is equal to 0. Therefore, integrating around the loop in Figure 2.1 yields a second equation that allows the solution/substitution of $j_w$ and $j_s$ into the average velocity equation.

$$\frac{j_w}{\sigma_w} - \frac{\sigma B u_{avg}}{\sigma} + j_s = (S - S_w) \frac{dT}{dy} - u_{avg} B \quad (2.15)$$

Here the wall terms $\sigma_w$ and $S_w$ appear, which are the wall electrical conductivity and the wall Seebeck coefficient, respectively. Note that in some data, especially data referenced for this work\textsuperscript{[48]}, the Seebeck coefficient is reported with respect to some predetermined metal, such as stainless steel. Therefore, the data already gives relative thermopower with respect to a certain wall material, and the $(S - S_w)$ terms reduces to just $S$. Alternatively, it may be necessary to recreate the absolute thermopower from a relative value in order to find the thermopower relative to a different wall material. Using Eqns. 2.14 and 2.15 to eliminate $j_w$ and $j_s$, the average velocity is given by

$$u_{avg} = \frac{H_a - \tanh(H_a)}{H_a + C \tanh(H_a)} \left( \frac{S - S_w}{B} \frac{dT}{dy} - \frac{1 + C}{\sigma B^2} \frac{dP}{dz} \right) \text{ with } C = \frac{a \sigma}{t \sigma_w} \quad (2.16)$$

This expression for the average velocity of TEMHD flow shows how the liquid velocity reacts to a change in essentially all of the relevant parameters of the system. Note that this result is for even heating of a long channel. Though non-uniform heating results in some slightly different flow conditions, this result is sufficient to inform the design of a high velocity flow system, and is accurate for the proof of concept case tested.

2.2 System Design

The concepts for a high velocity TEMHD flow system were heavily based off of the success of the LiMIT apparatus\textsuperscript{[35,40,43,49,50]}. The goal of this experiment is to adapt the basic LiMIT trench flow to support heat fluxes of up to 10s of MW/m$^2$. This range corresponds to beam heating and high intensity plasma heating such as strong divertor heat stripes. Contemporaneously, it is important that this system remains compact, which means utilization of space and debris mitigation become important subjects. After discussion on different systems
that can stimulate high velocity flow, it was decided a relatively simple geometric solution could provide the answer.

As seen in Figure 2.4, the modified trench design incorporates a symmetric ramp. While lithium can flow freely in a loop from the outlet around to the inlet of the domain shown, the driving force is developed predominantly in this region. 2 mm wide trenches exist for the duration of the ramp. At the beginning and end of the trench domain, the trenches are 10 mm deep, similar to previous LiMIT tests. The thermal gradient that develops here helps to push the flow into the shallow region on the inlet side and pull it out from the outlet side. The characteristics of incompressible flow dictate that mass flow rate through a given cross-sectional area must remain constant. Therefore, as the flow moves toward the shallower regions of the ramp, velocity will drastically increase. This is an interesting application of the nozzle effect, where adjustment of cross-sectional area is used to control fluid flow. Additionally, this design helps protect against debris buildup. In deep channel flow, debris can fall out of solution and accumulate, but in shallow, rapid velocity regions, debris is carried through and does not deposit as readily. Therefore, the shallow area simultaneously provides high velocity flow and debris mitigation in the high heat flux region of interest.
Based on this trench design, some simple calculations provide a goal velocity for lithium flow. The following is based off a 200 W ion beam that can be used to irradiate the lithium flow for neutron generation (see Section 2.7 for more information on this application). Heat transfer rate \( Q \) is given by

\[
Q = \dot{m}C_p\Delta T
\]  

(2.17)

Where \( \dot{m} \) is the mass flow rate of the lithium, \( C_p \) is the specific heat capacity, and \( \Delta T \) is the temperature difference caused by the heat transfer. In order to preclude the possibility of rapid lithium evaporation, the temperature increase should stay below 100 °C to keep the lithium temperature below a peak of 400 °C. Therefore, using the heat capacity of lithium of 3.58 kJ/kg-K, and the 200 W input heat, rearranging the above yields a required mass flow rate of \( 5.6 \times 10^{-4} \) kg/s. To determine required velocity, use

\[
\dot{m} = \rho u A
\]  

(2.18)

Where \( A \) is the cross sectional area of the flow. The beam spot is approximately 3 mm wide, the depth of trenches at the shallowest part of the ramp is designed to be about 0.5 mm, and the density of liquid lithium is 535 kg/m\(^3\). This yields a required flow velocity of

\[
u = 69.8 \approx 70 \text{ cm/s}
\]  

(2.19)

While this velocity is quite high, it is well within the possibility of TEMHD-driven flow. A significant amount of prior LiMIT testing was conducted without any incident heat flux. Rather the system was heated via plate or cartridge heating from the below the trenches, and the thermal gradient was supplied by cooling channels passing through the middle of the device. While the topside temperature gradient would eventually diminish due to lack of heating (usually on the order of minutes), flow could be sustained from the bottom temperature gradient. Air cooling on previous LiMIT tests was sufficient to maintain a thermal gradient on the order of 2600 K/m\(^3\)[39], which corresponds to about 26 K over the 10 mm trench depth. While future tests of the system may need more advanced cooling systems, for now it is assumed that air cooling is able to provide this level of thermal gradient. Moreover, better cooling would lead to a larger temperature gradient, which acts to increase flow velocity.
From the design decisions and assumptions made, the last step is deciding on a magnetic field. The relationship between average flow velocity and magnetic field is more complex than some of the other direct or indirect dependencies, as seen in Eqn. 2.16. Figure 2.5 shows a plot of the average velocity versus the magnetic field based on Eqn. 2.16 with the parameters used listed in Table 2.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>2 mm</td>
<td>Characteristic length</td>
</tr>
<tr>
<td>a</td>
<td>1 mm</td>
<td>Half trench width</td>
</tr>
<tr>
<td>t</td>
<td>1 mm</td>
<td>Wall thickness</td>
</tr>
<tr>
<td>σ</td>
<td>3.6x10^6 S/m</td>
<td>Electrical conductivity of lithium</td>
</tr>
<tr>
<td>σ_w</td>
<td>1.3x10^6 S/m</td>
<td>Electrical conductivity of stainless steel</td>
</tr>
<tr>
<td>µ</td>
<td>5.03x10^{-4} Pa-s</td>
<td>Dynamic viscosity of lithium</td>
</tr>
<tr>
<td>S</td>
<td>2.5x10^5 V/K</td>
<td>Seebeck coefficient for lithium</td>
</tr>
<tr>
<td>S_w</td>
<td>0</td>
<td>Seebeck coefficient for wall (stainless steel is reference for S above)</td>
</tr>
<tr>
<td>dT/dy</td>
<td>2600 K/m</td>
<td>Temperature gradient into trench</td>
</tr>
</tbody>
</table>

This figure shows that the maximum velocity is achieved with a magnetic field of approximately 0.015 – 0.02 Tesla, equivalent to 150 – 200 Gauss. Additionally, the ideal average velocity is on the order of 140 cm/s, well above the velocity required for effective heat removal.
In the plot, the term including the temperature gradient is neglected. Ideally, in evenly heated flow, the pressure gradient term will go to 0 as the flow reaches steady state, especially since the flow continues in a loop, meaning inlet and outlet pressures are identical. The pressure gradient is in fact non-zero when there is uneven heating, like the beam heating case, because local acceleration will pump a local pressure gradient. However, while including the term does change the maximum velocity magnitude slightly, the change in B-field position of the peak is almost negligible, and therefore does not influence the choice of operating magnetic field.

2.3 Experimental Setup

The compact high velocity flow base module is shown in Figure 2.6. It has a compact reservoir loop that is used to store and recirculate lithium flow. It holds ample lithium volume for a continuously refreshing flowing surface, and also allows high temperature lithium to cool as it travels around the loop, before being subjected to high heat fluxes again. The backside of the lithium loop is also used for lithium injection. Two slots are cut out to hold the permanent magnets.
Figure 2.6 – Proof of concept compact TEMHD flow system as built. Final application will be covered, as seen in the leftmost image, to eliminate splashing or spilling.

Previous LiMIT designs utilize external electromagnets, but switching to permanent magnets significantly reduces required power systems, cuts cost, and saves space, allowing the B-field to be contained in the apparatus. When inserted, the magnetic field midway between the magnets in the lithium flow region registered at approximately 200 Gauss, which should give near maximum flow velocities. It should be noted that these magnets are specifically high Curie temperature magnets, meaning they will retain their magnetic permanence at high temperatures. Normal permanent magnets tend to degrade and lose their permanent magnetism as the temperature climbs to the Curie temperature, and instead switch to induced magnetism. The permanent magnets used here, however, have a Curie temperature of approximately 800 °C, and can therefore reliably operate as high as 550 °C.

A modular trench insert was fabricated and placed in the deep reservoir between the 2 magnet slots. This design conveniently allows for rapid design iteration, which was experienced firsthand in initial testing. The first set of fabricated trenches is seen in Figure 2.7a.

Figure 2.7 – Evolution of the trench insert. a) Initial thin trenches did not allow ample filling or good wetting. b) The trenches were widened by removing the first, third, and fifth walls of the initial piece.
A total of 4 cm long, the 1.25 mm wide trenches tapered from 10 mm depth at the ends to 0.5 mm depth in the center. During the first attempts at filling and operating the system, it was quickly seen that the surface tension of the lithium was too high to allow effective filling and wetting of the trenches. Impurity layers on the lithium also impeded ample trench filling. Therefore, the modular design of the system was utilized, the trench insert was removed and cleaned, and the trenches were widened. This was done by simply removing the first, third, and fifth trenches, resulting in the insert shown in Figure 2.7b. This yielded approximately 2.5 mm trenches and 1.25 mm walls, with the sides of the reservoir now acting as trench walls as well. Due to machining limitations, the middle trench became slightly larger, on the order of 3.5-4 mm. To check if this would impact flow, the new parameters were input into Eqn. 2.16, and the results can be seen in Figure 2.8.

![Figure 2.8](image)

**Figure 2.8** – Adjustment of the flow velocity curve versus the magnetic field, based on the system parameters as built. While the peak shifts, the magnetic field used should still support ample lithium flow speed.

Though the peak velocity has shifted slightly, the ideal-case average flow velocity is still more than enough. It is worth noting here that eventual operation of the device, when closer to a final design, will entail the trench piece being inserted “upside down” so that the ramp faces the bottom of the reservoir, as seen in the CAD drawings in Figure 2.9. This allows for better constraint on the flow and will minimize the possibility of liquid lithium upwelling when the velocity quickly increases in high heat flux conditions. While it may increase the clogging risk based on the debris and impurities present in the system, future iterations already plan on impurity control to mitigate this risk. For the proof of concept test, the trenches were inserted
face up for flow visualization, and as will be seen in the following sections, impurities (though they did impede flow at times) actually allow velocity tracking and imaging of flow characteristics.

![Figure 2.9](image1.png)

**Figure 2.9** – The compact flow base module as designed, showing the insertion of the trench piece so that the flow is constrained in the bottom of the device.

Cooling lines inserted into the main lithium loop module provide the temperature gradient. The lithium loop module is then inserted into a heater box containing 4 Watlow cartridge heaters. For the proof of concept test, cooling of the latent heat of the system develops the temperature gradient, while in later testing, a top beam or plasma heat flux will be added. The cooling system is shown in Figure 2.10.

![Figure 2.10](image2.png)

**Figure 2.10** – Design of the cooling system as built, showing how the thermal gradient develops.

A strong attempt was made in building and testing this system to use as much available infrastructure as possible. Luckily, inventive vacuum chamber stacking is one of the specialties of the CPMI, resulting in the setup seen in Figure 2.11.
Mounted on the SLiP chamber previously used for vertical LiMIT testing, the gold chamber housed the compact lithium loop setup. The chamber to the side provided internal connections for the cooling lines via Swagelok connectors, power for the cartridge heaters, and connections for the thermocouples used to measure temperature. The job of the thermocouples is twofold. First, they can measure the temperature gradient if well placed at the top and bottom of the trenches. Second, the thermocouples are intuitively placed downstream of expected flow. Therefore, as cooling is turned on and TEMHD flow begins, an increase in the thermocouple temperature will be seen as hot lithium is driven downstream. If visual observation is difficult or impossible, this temperature increase can imply that the lithium is actually flowing. The large assortment of extensions and chambers on top of the main module is for the lithium injector. The manual ramrod injector developed for the MCATS chamber was used in order to have good control of the lithium volume injected.
2.4 COMSOL Flow Modeling

2.4.1 Domain and Physics Setup

As the final proof of concept designs were fabricated and prepared for testing, detailed modeling of the system was carried out using COMSOL Multiphysics. Development of this fully coupled model allows for the evaluation of flow characteristics using realistic conditions and, if validated by experimental observation, provides a means of design iteration without physically building each attempt.

![COMSOL model domain with trench insert and flow inlet and outlet regions.](image)

The COMSOL model domain was set up to capture the majority of the system physics while remaining within the bounds of computational constraints. As seen in Figure 2.12, the model geometry accurately reflects the adjusted trench design. The 4 trench walls are each 1.25 mm thick, and these enclose 3 trenches, 2 of which are 2.5 mm wide, and one that is 3.75 mm wide. The trenches taper from 10 mm deep to 0.5 mm deep as in the final test module. The COMSOL domain includes the 4 cm trench region, along with 1.27 cm (0.5 in) of open reservoir flow on the leading and trailing edges of the trenches. This allows for some insight into how the flow develops as it enters and leaves the trench structure. A periodic flow condition is imposed between the 2 sides of the domain to mimic the effect of the reservoir. If turbulent or swirling conditions develop (hint: they do), it is important to see how they affect entering and exiting trench flow. Since it is not computationally feasible to include the entire lithium loop reservoir, the behavior of a looping system is maintained by the periodic flow condition.
This simulation includes the Electric Currents (EC), Heat Transfer in Fluids (HT), and Laminar Flow (LF) physics modules. The TEMHD driving force is primarily incorporated through an external current density applied to the EC module, and a resultant volume force in the LF module. As mentioned earlier, the current density is given by Ohm’s Law adjusted to include a term representing the thermoelectric effect

\[
\vec{j} = \sigma (\vec{E} + \vec{u} \times \vec{B} - S \nabla T)
\] (2.20)

The HT module solves for the thermal gradients in the system, which provide the impetus for the thermoelectric current and TEMHD driving force. It includes both fluid heat transfer and solid heat transfer components. The fluid heat transfer physics includes convection and advection solvers that iterate based on results in the LF module. The domain is initialized to 723 K (450 °C) everywhere, close to the initial temperatures of the experimental trial. It is “air-cooled” starting at t = 0 seconds by a convective heat flux on the bottom surface of the domain with a heat transfer coefficient of 500 W/m²-K. In this proof of concept case, there is no additional external heat flux to mimic extra heating. The thermal gradients are passed to the EC module and used in a user-defined external current density. To input the components correctly, it is helpful to directionally break down the current density equation above. For this coordinate system (note that it differs from the derivation of average flow speed in Section 2.1),

\[
\left( \vec{u} \times \vec{B} \right) = (u\hat{x}, v\hat{y}, w\hat{z}) \times B_0\hat{x} = (0\hat{x}, wB_0\hat{y}, -vB_0\hat{z})
\] (2.21)

Where \(B_0\) is the magnitude of the magnetic field, which is 200 Gauss. Plugging this into the current density, splitting it into components, and recognizing that the electric field component is 0 yields

\[
j_x = \sigma (-S \nabla T_x)
\] (2.22)

\[
j_y = \sigma (wB_0 - S \nabla T_y)
\] (2.23)

\[
j_z = \sigma (-vB_0 - S \nabla T_z)
\] (2.24)
Finally, the LF module solves for the fluid flow in the domain. As mentioned, periodic flow conditions exist in the y direction. The top boundary of the fluid domain is modeled as a slip condition, simulating the free surface flow. Everywhere else, typical non-slip boundaries are used at the walls. The TEMHD force is included as a \((\vec{J} \times \vec{B})\) volume force applied to the fluid domains.

\[
\vec{F} = (\vec{J} \times \vec{B}) = (j_x\hat{x}, j_y\hat{y}, j_z\hat{z}) \times B_0\hat{x}
\]  

\[F_x = 0 \tag{2.26}\]

\[F_y = j_zB_0 \tag{2.27}\]

\[F_z = -j_yB_0 \tag{2.28}\]

Computational constraints, namely 16 GB of RAM, required the use of a segregated solver for a majority of these simulations. A fully coupled direct PARDISO solver was demonstrated as feasible, but RAM utilization was maximized, and system performance slowed greatly. As such, the fully direct solver actually ran slower than the segregated method, though with ample RAM, it should outpace the segregated solver. The segregated solver calculates the electric currents using an iterative conjugate gradients method, while the pressure, temperature, and velocity fields are calculated using a direct PARDISO solver. The most effective way to set up the segregated solver is to first use the direct solver for the temperature, next use the iterative solver for the electric currents, and finish with the direct solution of pressure and velocity. This mirrors the steps taken above in deriving the TEMHD input.

2.4.2 Flow Results of Proof of Concept Design

After experimenting with simulation run time, it was found that the flow conditions are generally fully developed by 2 seconds. So while the simulations can run longer than that, it is not necessary, and more of the same behavior is just repeated as the simulation progresses. Figure 2.13 shows the velocity streamlines of flow development over the course of 2 seconds.
Figure 2.13 – COMSOL results (every ~0.5 seconds) of proof of concept test (no top heat flux) showing velocity streamlines, color mapped by velocity magnitude (red is max positive, blue is max negative). The 2 circles in the final frame outline the regions compared in the experimental analysis.

Each image is half a second farther through the simulation. The color map of the streamlines and accompanying legend represent the velocity of the flow, in meters per second. As the model progresses, turbulent eddies and vortices appear in the flow. This turbulence is caused by the behavior of the temperature gradient. While predominantly in the z direction, Figure 2.14 shows that there is some deviation from vertical.
As a result of the changing thicknesses of the solid ramp and the relationship that has with heat transfer to the fluid, there are non-zero x and y directed thermal gradients. This in turn drives eddies and turbulence in the flow. However, the final temperature distribution in the model verifies the assumed temperature gradient that led the design decisions mentioned earlier. The temperature slice through the trench in Figure 2.15a shows there is a temperature difference of approximately 25 °C from the top of the trench to the bottom, which was expected. Additionally, a slice displaying the z-directed temperature gradient (Figure 2.15b) shows a distribution between about 6000 and 2000 K/m, exactly what has been experimentally achieved in early LiMIT tests and what is necessary to drive this high velocity flow.
Figure 2.15 – a) Temperature profile of the system at the end of the simulation, proving the expected temperature differences across the liquid-solid interface. The color map give temperature in Kelvin. b) Z-directed temperature gradient at the end of the simulation, verifying expected magnitudes. The color map gives temperature gradient in Kelvin per meter.

Ultimately, while the zero top heat flux case predominantly displays turbulent developments in the flow, the velocity surface plot in Figure 2.16 shows there should still be defined unidirectional flow through the shallow, high velocity area of the trench insert. It seems that the slightly wider trench is more affected by the turbulent flow on either end, but the smaller edge trenches reach a sustained flow in the negative y direction, with a maximum velocity of 9 cm/s.
Figure 2.16 – Velocity surface plot of the proof of concept case. The color map gives velocity in meters per second. The highest positive (to the right) velocity is red, and the highest negative (to the left) velocity is blue.

2.5 Experimental Results and Code Validation

At this point, turbulent flow conditions were expected in the proof of concept design, but sustained unidirectional flow should be possible. Therefore, physical system testing proceeded. After installing all components and checking all heating, cooling, and thermocouple connections, the system was heated. The lithium loop module was heated to 450 °C while the lithium injector was brought to approximately 275 °C. The ultra-torr feedthrough on the side of the main module (seen in Figure 2.11 above) was connected to the lithium loop apparatus. To fill the device, it was pulled close to the injector side of the chamber when the lithium was heated, and pushed back toward a viewing window after filling and wetting was achieved. Figure 2.17 shows the trench inserts and the magnets (and one of the cooling lines) as installed but not yet pumped to vacuum.
When the lithium was injected using the manual injection system, there was a heavy coating of impurity. As seen in Figure 2.18, this impurity coating threatened to inhibit wetting even before reaching around the reservoir to the trench insert.

The test was not abandoned, and luckily repeated percussive impact to the ultra-torr feedthrough was effective in breaking up the scaling and allowing fresh lithium to wet throughout the reservoir and trenches. The filled trenches are shown in Figure 2.19.
Figure 2.19 – A section of the trench insert well filled with lithium. Some impurity scaling can still be observed on the top of the lithium.

2.5.1 Flow Results and Characteristics

As soon as the compressed air cooling was activated, flow was observed in the trenches and reservoir. Trench flow was seen on either side of the shallow region, and the center region stayed filled, so lithium flow was continuing across the shallow, high velocity area. As expected from the COMSOL model, the flow developed highly turbulent eddies and vortices, especially at the exit of the trench structure. Cell phone video recording was used to record flow in hopes of recovering flow velocity measurements. While the scaly layer was frustrating for the wetting stage, once the layer was broken up, chunks of impurities floated nicely on the surface, allowing for flow visualization. Tracking of impurities was done post experiment using the tool ImageJ to analyze the videos frame by frame. The pixel distance an artifact moved over the course of several frames was rectified with the motion of the camera and equated to a physical distance based on the pixel size of the trenches in the image. Using this method, several particle velocities were identified.
Figure 2.20 – Particle tracking in the trench region provides experimental velocity characteristics. The red circles track specific particles moving through the trench.

Figure 2.21 – Particle tracking in the turbulent eddy region provides additional velocity characteristics. The red circle tracks a particle that gets caught in the eddy flow.

While the movies provide the best visualization, there were 2 strong cases of flow that could be easily represented in still images. These are shown in Figure 2.20 and Figure 2.21. The remainder of the identified particles, though visible under close inspection, did not reproduce well in images for proof of flow. The case in Figure 2.20 shows sustained trench flow coming from the shallow flow region at the top of the image and progressing downward as expected. Each particle travels approximately 1.9 mm in 2/15 of a second, which corresponds to 1.4 cm/s. Figure 2.21 shows an example of a particle that is caught in the swirling eddy flow just outside the trench structure. Over the course of 1/15 of a second, this particle drifted into a region of higher velocity flow coming out of a trench and traveled about 2.8 mm. This is a 4.2 cm/s velocity. The particle then continued to swirl back up toward the trenches and spin. Other particles scattered throughout the analyzed viewing area yielded velocities between 1.3 to 2.86 cm/s.
2.5.2 Comparison to COMSOL Model

Comparison of the experimental flow to the predictions of the COMSOL model show impressive agreement. The experimental system immediately developed eddies and turbulent flows that mirrored those that quickly developed in the simulation. COMSOL Multiphysics is a well-developed software, and its methods and modules have had extensive verification. Furthermore, the experimental agreement provides model validation. The blue circles in Figure 2.13 show the location of the 2 tracked impurities above, and Table 2.2 gives the speeds from the images and the model.

Table 2.2 – Comparison of Velocity Characteristics between Model and Experiment

<table>
<thead>
<tr>
<th>Region</th>
<th>Experiment</th>
<th>COMSOL Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep part of trenches</td>
<td>1.4 cm/s</td>
<td>1 - 5 cm/s</td>
</tr>
<tr>
<td>Turbulent eddy region</td>
<td>4.2 cm/s</td>
<td>1 - 6 cm/s</td>
</tr>
</tbody>
</table>

The trench flow is tracked into the deeper areas of the trenches, where flow velocity drops off quickly, so a relatively slow velocity was expected. The turbulent eddies showed velocities anywhere from about 1 to 6 cm/s, so the results sit squarely in that range. The other tracked particles all match model velocities seen, and it is important to note that the turbulence is, by definition, not steady. Velocities increase and decrease, and eddies form and disappear, and this qualitative behavior was well documented throughout the tests. It is also important to note that the tracked velocities will slightly underestimate the true liquid lithium flow velocity. Massive particles can get dragged by the flow, but they are large enough that they will not match the flow conditions precisely.

2.6 Model Extension to Fast Flow Conditions

2.6.1 Domain Adjustment and Parameters

Now that the model has been validated by experimental evidence, it can be modified to account for future test parameters. The next step is including a topside heat flux in order to drive
high velocity lithium flow. This is done via inclusion of a heat flux component in the HT module. The shape mimics a heat stripe along a divertor or from a linear electron beam (like the one at CPMI used for LiMIT tests), though it can be easily adjusted to resemble more focused beams for future application. The heat flux is added as a Gaussian profile, with the form

\[ q = q_{\text{max}} \exp \left( \frac{-(y - y_{\text{centerpoint}})^2}{FWHM^2} \right) \left[ \frac{W}{m^2} \right] \]  

(2.29)

Here, \( q_{\text{max}} \) is the maximum value of the curve, \( y_{\text{centerpoint}} \) is where the peak is centered, and \( FWHM \) is the full width at half maximum of the Gaussian distribution. Using a \( q_{\text{max}} \) of \( 4 \times 10^6 \), a \( y_{\text{centerpoint}} \) of 1.835 cm (center point of the shallow region in the model), and a \( FWHM \) of 5 mm, the heat stripe appears as seen in Figure 2.22.

![Figure 2.22](image)

**Figure 2.22** – First resolved time step of the adjusted model, showing the immediate distribution of the additional heat flux and how it begins to affect the temperature distribution. The color map is temperature, given in Kelvin.

### 2.6.2 Fast Flow Model Results

The addition of the top heat flux created faster flow conditions, as expected. The 2 second simulation was repeated, and frames at roughly 0.5 second intervals are given in Figure 2.23.
Figure 2.23 – COMSOL results (every ~0.5 seconds) of the high heat flux model, showing velocity streamlines color coded by velocity magnitude. Predominant flow direction is in \(-y\) (flow progressing toward the left), as marked by the steady dark blue streamlines.

Since the beam heat input is quite large, the temperature gradients that develop as a result of its presence quickly begin to dwarf those provided by the general cooling of the system. Therefore, the \(y\) directed thermal gradients dominate any \(x\) and \(z\) thermal gradients, allowing the flow to develop much smoother characteristics. Some early turbulence is quickly smoothed by high velocity flow through the trenches. It can also be seen that the center trench exhibits much stronger unidirectional flow than the case with no external heat flux, necessary for application of this system in a high heat flux regime. The surface velocity plot in Figure 2.24 displays the much smoother flow trends, and gives a maximum trench velocity of 60 cm/s.
Figure 2.24 – Velocity surface plot of the high heat flux model. Sustained flow on the order of 60 cm/s toward the left side of the domain is shown by the dark blue colors in each of the 3 trenches.

The slight velocity undershoot from the required 70 cm/s may be due to transient effects of the pressure gradient as flow develops, as well as a pressure gradient term from the high local heating and flow acceleration. The pressure gradient term has a negative effect on the average velocity, so in the region directly downstream of the heating, there will be a pressure gradient pushing back against the flow.

Figure 2.25 – The final frame temperature plot of the high heat flux simulation shows lithium temperature stays within manageable limits and does not enter a high evaporation regime. The color displays temperature in Kelvin.

The results of the temperature increase in the system are encouraging. It can be seen from the plot in Figure 2.25 that the temperature of the lithium never exceeds 723 K (450 °C), which would be the 100 °C increase limit desired during operation. The trench surfaces get warmer, with a maximum of 875 K (602 °C), but this is well below a damaging temperature for
stainless steel. The heat flux increases the trench temperature quickly, and it begins to level off well before the 2 second mark, so this should not be a concern. It is also likely that in final tests of the device, either lithium overfill or flipping of the trench module will keep the trenches submerged in liquid lithium, improving heat transfer and lowering peak trench temperatures.

2.7 Discussion and Application

This chapter presents a novel method of utilizing the TEMHD effect to develop high velocity self-driven liquid lithium flow in a tightly controlled area. In the initial testing of the proof of concept device, the high temperature (450 °C) meant heavy lithium evaporation was present, blocking out the viewport window after some time. In the final application of this device, a cover will be applied to contain the entire system, which will mitigate evaporation and splashing seen in these tests. Additionally, impurity control will eliminate flow blockage due to passivated lithium scaling on the surface of the flow.

Based on the designs for the system, the fully coupled COMSOL model solves for flow conditions along the ramping trench insert. The agreement in the proof of concept setup prompted an examination of high heat flux conditions. The model successfully demonstrates that high velocity liquid lithium flow should result, with little turbulence. Future design ideas can be tested in the model without requiring extensive physical testing, increasing speed and ease of the iterative design process.

This high velocity lithium flow system was designed for 2 important applications. First, in fusion applications, PFCs can benefit greatly from fast flow. The high velocity of low-Z lithium allows for high heat removal and rapid surface replenishment, which will lower the total lithium temperature and minimize evaporation. Techniques such as this ramp flow (and other possibilities that can be modeled in the simulation) can be used to effectively control lithium velocity based on heat flux, magnetic field, and system needs. Second, the design will find commercial use in neutron generation applications. High intensity deuterium beam heating in the center of the thinnest flow region will drive high velocity flow and enable advanced D-Li reactions to make neutrons without the use of radioactive tritium. The compact and self-contained nature of the system allows it to be modular and scalable.
CHAPTER 3 – DRYOUT MODELING

3.1 Background

Until this point, computational studies\textsuperscript{[38]} of the flowing liquid lithium in the LiMIT system have consistently constrained the lithium in a rigid domain. Indeed, even the simulations in Chapter 2 are guilty of this (see Chapter 6 for a discussion on why this is believed to be acceptable). While this may be fully accurate if the liquid is truly constrained, such as in pipe flow, the solution lacks completeness when an open surface exists. Fluids slosh around when forces act upon them, and this behavior cannot be captured when a rigid domain is used. The usual solution is to make the top surface a slip boundary condition, which mimics an open surface by eliminating the frictional force from the walls. This treatment is generally effective in describing flow conditions, and has been used to model and predict flow velocities in LiMIT trenches, as seen in Figure 3.1\textsuperscript{[38]}.

![Image of velocity distribution](image1.png)

\textbf{Figure 3.1} – Velocity distribution from \cite{38} simulating the flow in an early design of LiMIT trenches.

As plasma flux impinges on the surface of the lithium flow, the lithium experiences a high local acceleration where the plasma flux is greatest. The same effect of incompressible flow that increases the flow speed in Chapter 2 as the flow height diminishes now works in reverse. The acceleration and velocity increase of the flow leads to a depression of the lithium surface and pileup of the lithium downstream. This phenomenon is known as lithium dryout, and is depicted in the diagrams in Figure 3.2.
Dryout in a liquid PFC system can be severely damaging, especially in a LiMIT-type trench array. As the lithium level decreases, the tops of the trenches may become exposed. If this occurs, the solid metal is now directly impacted by the plasma, which could lead to overheating and the exact damage a liquid metal system is built to avoid. Additionally, the thinner lithium surface is now absorbing the same heat flux as with a fully filled trench, leading to a larger increase in temperature and high lithium evaporation.

There are several potential mitigation strategies for liquid lithium dryout, including trench shaping, partial trench removal, and addition of a constraining mesh. Trench shaping entails narrowing the height of the trenches in regions of high plasma heat flux in order to compensate for the increased velocity. This is similar to the methods used in Chapter 2, though not as drastic. Another option is allowing and planning for the plasma depression of the lithium. In this case, the trench walls are reduced in height to follow the depression level, keeping them submerged in the liquid lithium. Since this depression will cause pileup downstream, it would be wise to allow a larger outlet to accommodate and alleviate the lithium pileup. Finally, a third option is the addition of a thin mesh to the tops of the trenches. Lithium has a very high surface tension, so this mesh could constrain the surface of the lithium without impeding bulk flow. The mesh may not be well protected, however, as only a thin film will cover the wiring (especially in the highest heat flux regions), so the mesh may degrade over time and need replacement. This is still a more desirable outcome than damage to the bulk solid first wall components. Illustrations of these options are shown in Figure 3.3.

Figure 3.2 – A diagram of the lithium dryout phenomenon. When high local heat flux impacts a flowing lithium surface, local acceleration causes a depression of the lithium surface, and pileup downstream.
3.2 COMSOL Modeling

The term dryout is commonly used to describe the phenomenon that occurs as a liquid reaches its critical heat flux and begins to exhibit film boiling\textsuperscript{[51]}. While study of this effect has been applied to liquid metals, the application is usually confined to liquid metal cooling of sodium or lead fission reactors\textsuperscript{[52,53]}. As liquid metal PFCs become more popular, some studies have investigated film boiling dryout with respect to fusion applications\textsuperscript{[54,55]}. The type of dryout investigated here, however, is relatively limited in its relevance, and no free surface liquid lithium technology has progressed far enough to warrant further scrutiny into this effect. As mentioned earlier, no trench flow models have included true open surface flow, though the velocities and accelerations seen in simulation results, as in Figure 3.1 above, imply a dryout condition would occur. To that end, COMSOL Multiphysics was used here to develop a 2D simulation of free surface lithium flow under high heat flux, with the goal of replicating the dryout phenomenon and taking steps to alleviate it.
3.2.1 Theory and Domain Setup

The simulation is performed in a 2D simplified domain in COMSOL. The overhead and lack of optimization towards fluid flow problems in COMSOL makes 3D simulations extremely cost ineffective to run and very error prone. Therefore, a 2D slice of a 3D trench is modeled in the domain shown in Figure 3.4.

![Figure 3.4](image)

Figure 3.4 – 2D COMSOL domain used to simulate the dryout phenomenon. The top surface is modeled as a free surface and the mesh is allowed to deform to follow liquid motion.

In order to accurately model the behavior of the free surface, the Laminar Flow (LF) module is coupled with the Moving Mesh (MM) module. In the LF module, the inlet and outlet are set as pressure inlet and outlet conditions. An attempt was made to link the inlet and outlet using a periodic flow condition, but the dryout deformation passing to the inlet side of the domain eventually caused errors to amass and the solution to diverge. The top surface is again a free surface modeled as an open boundary with 0 normal stresses on the surface. Since the development of the thermoelectric current is dependent on the junction between the lithium and a wall, and inherently 3-dimensional (looping into and out of the page in the domain view), the full coupling between heat transfer and electric currents cannot be included via modules in this model. Instead, a Gaussian volume force term is included in the LF module that takes the entirety of the TEMHD effect into account. In a 3D domain, a Gaussian heat flux leads to a thermoelectric current, which in turn is used to calculate a volume force. In COMSOL post-processing, the volume force data was examined. The vertical volume force is a combination of the velocity and fluid effects, as well as the errant thermal gradient effects. From 3D simulations, the volume force data was extracted and input into this 2D domain.
The important improvement in this work is the addition of the moving mesh. The interface allows the free surface to deform in response to the fluid flow on the top surface. This allows the mesh movement to be coupled with the driving force provided by the TEMHD effect. Typically, physical systems are set up and solved computationally in one of two coordinate systems. The spatial coordinate system, known as the Eulerian formulation, fixes the coordinate axes in space, and the material coordinate system, known as the Lagrangian formulation, fixes the coordinates to the reference material and follows the material as it deforms. For fluid solutions, the Eulerian formulation tends to be more convenient, since following the particles becomes quite computationally intensive. However, since the grid points are fixed to a spatial system, an Eulerian method cannot follow moving domain boundaries, which are a staple in open surface flow. One way to get around this problem is to use a convenient feature that is always included in COMSOL – the mesh. The mesh points created in COMSOL have a direct mapping to material domain points. Therefore, if the mesh were to deform and follow the mobile domain, it is possible to use an Eulerian mapping to solve for a deforming Lagrangian-type system. This is known as an arbitrary Eulerian-Lagrangian process, and it is included as the solver in the MM module[56]. As the domain deforms, the mesh is stretched and compressed along with the domain motion. While this deformation can cause degradation of the mesh quality that can lead to a buildup of solver error, small disturbances can be effectively solved with a fine enough mesh.

Implementation of the MM module requires choosing what boundaries and domains are allowed to deform, and in what way. For this system, there is only one domain, which is allowed free deformation. In order to constrain that deformation, and hold it in its trench shape, prescribed displacements are used on the edges. The bottom surface is a no slip surface that has a prescribed displacement of 0 m in both the horizontal and vertical directions. This keeps the bottom fixed at all times. The inlet and outlet edges on the sides of the domain have a prescribed displacement of 0 m in the horizontal direction, and no constraint vertically. This allows the edges to follow any vertical motion in the domain, such as dryout or pileup, while still acting as a fixed inlet or outlet. The free surface on the top, meanwhile, is modeled using a prescribed mesh velocity. Velocities solved by the laminar flow module are coupled with this step, and the mesh deforms to match the true behavior of the fluid in the horizontal and vertical directions. A Winslow smoothing algorithm is chosen to deform the mesh, which leads the software to solve
\[
\frac{\partial^2 X}{\partial x^2} + \frac{\partial^2 X}{\partial y^2} = 0 \quad \text{and} \quad \frac{\partial^2 Y}{\partial x^2} + \frac{\partial^2 Y}{\partial y^2} = 0
\]  \hspace{1cm} (3.1)

Where X and Y are the material frame coordinates, and x and y are the spatial degrees of freedom\([56]\). In a 2D model, there is less physics to solve, so a direct MUMPS methods is used to solve the fully coupled system.

3.2.2 Model Results

The model was run for up to 3 seconds after heat flux impingement begins. Two separate cases were examined, a slow flow case with 1 cm/s velocity, and a fast flow case where the velocity is 10 cm/s. These can be thought of as low heat flux and high heat flux cases, as the volume force is adjusted accordingly based on the amount of flux the flow speed can handle. The system is initialized with aforementioned velocities, as though lithium flow was established using an alternative heat flux, such as heaters on the bottom of the trench. The impingement heat flux is centered at 0 centimeters in the domain, and starts at \(t = 0\) seconds.
Figure 3.5 – Frame-by-frame (every 0.5 seconds) results of slow flow dryout development. Initial velocity is 1 cm/s. The color map shows flow velocity, and the dotted line marks the trench level/nominal lithium level.

The slow flow case is shown in the series of images in Figure 3.5. Again, the colormap represents lithium velocity. As the simulation begins, the dryout begins to form in the center, directly under the highest heat flux. This is due to the preferential heating of the lithium in the depressed region, which is then accelerated by the large thermal gradient resulting from passing through the heat stripe. The dryout is then propelled down the trench by the flow. Lithium pileup occurs downstream of the high heat flux region, as high velocity lithium accelerates into slower downstream flow. As this reaches the end of the trench, spillover could occur, damaging other components that are not necessarily compatible with the hot liquid lithium. It is also interesting that as the dryout forms, there is upstream buildup that occurs during its transient development. This is due to lithium building up against the reduced cross-sectional area of the flow before accelerating through the high heat flux region. Additionally, as the initial heat flux...
impact depresses the lithium surface, the pressure from that quick acceleration actually extends in both directions. This causes upwelling on either side of the depression like when a rock impacts shallow water and the entire area around it wells up before splashing. This effect starts the upwelling, and the continuation of flow into these regions helps maintain this pileup observed.

Figure 3.6 – Frame-by-frame results (every 0.05 seconds) of fast flow dryout development. Initial velocity is 10 cm/s. The color map shows flow velocity, and the dotted line marks the trench level/nominal lithium level.

The fast flow case exhibits the same behavior, albeit faster than the slow flow tests. The set of images describing this case is given in Figure 3.6. Dryout forms under the heat flux region and extends downstream. The pileup quickly moves toward the end of the trench, and eventually leaves the domain, meaning half of the length of the trenches are potentially exposed. Note any lithium level below the initialized 5 mm will expose trench material.
3.3 Experimental Analogies

To determine how accurately the model reproduced the effect of dryout, it is important to examine experimental observations of the phenomenon. One prime example is in tests of the LiMIT apparatus in the SLiDE chamber at UIUC\textsuperscript{[49]}. In this case, a homemade electron beam system provides the heat flux, and a set of external electromagnetic coils provide the transverse magnetic field. As the e-beam is activated, a strong heat flux impinges on the lithium surface and begins driving flow.

![Figure 3.7 – Experimental observation of lithium dryout in LiMIT testing at UIUC. The left frame shows the stationary case before the electron beam heat flux instigates dryout and pileup seen in the right frame.](image)

In the beginning of the image sequence in Figure 3.7, lithium sits stationary slightly under the level of the trenches. As the flow begins, pileup immediately occurs downstream of the e-beam region. From the top of the frame to the bottom, the pileup is eventually drained out downstream through the return flow channels. Then it can be seen that the lithium depression formed in the high heat flux region persists as high velocity flow continues downstream of the impingement area. Due to fluid effects and inconsistencies in startup, there is a small ripple effect that oscillates across the trenches, and periodically slows down and bunches up the flow just upstream of the e-beam. This is similar to the upstream upwelling observed in the model. The dryout and pileup observed also directly mirror the effects developed in COMSOL.

Another example of dryout observed in experimental testing occurred in LiMIT tests under high heat loads at Magnum-PSI\textsuperscript{[43]}. Due to the more spread shape of the heat flux from the linear plasma device, an apt comparison is not as direct. However, lithium dryout and pileup are still clearly seen in the image in Figure 3.8.
Figure 3.8 – Infrared camera image of dryout beginning during LiMIT testing at the Magnum PSI linear plasma device. Trenches dry out progressively from the top of the image, the trenches becoming more visible as they heat up after the covering lithium level is removed.

3.4 Model Extension

From the above experimental comparisons, it is shown that the model provides a valid basis for engineering decisions regarding a solution to the problem. Of the potential mitigation strategies described above, perhaps the most straightforward is shaping the bottom of the trenches, either by machining or inserting additional material into the bottoms of the trenches. This method is also testable in the COMSOL model. The effect of trench insert shapes can be investigated before real world application. This allows for quick iteration through possible designs. Several different strategies were tested, and while they may have provided a solution to the dryout, in most cases the eventual return to original trench depth caused a small waterfall-like depression in the lithium surface. This may be acceptable since the depression occurs outside of the high heat flux area, but for now that effect was avoided.

It seems as though what may be one of the simplest ideas could actually become one of the best solutions to the dryout effect. A simple step increase in the height of the bottom of the trench provided multiple benefits in both the slow and fast flow cases. First, the extended region of the narrowed trench height directly combated the extended region of the dryout by compensating for the depression caused by the high velocity flow. Second, the slight offset from center allowed the buildup that generally occurs in front of underwater flow obstructions to be
placed directly underneath the area of strongest heat flux. The initial strong depression of the surface is directly opposed by this upwelling from the trench step. This can actually provide additional thermal protection of the underlying solid trenches. Third, the height of the pileup above the dryout is diminished. In other words, deviations from an average flow height are decreased. Instead the bulk flow from the center of the trench continuing downstream is raised slightly, which will not severely impact flow velocity and will also provide more protection for the trenches.

The strength of the above effects varies based on the magnitude of the trench-bottom height increase. This was investigated with the COMSOL model by running a parametric sweep over the height of the step increase. The height was varied from 0.3 mm to 3 mm (initial depth is 5 mm) with a step of 0.3 mm, and various metrics of the flow properties were extracted for each parametric solution. These parameters of the flow are diagramed in Figure 3.9 for clarity.

![Figure 3.9](image)

**Figure 3.9** – Diagram of different flow metrics measured during testing of trench shaping dryout mitigation techniques in the COMSOL model.

The results of the parametric analysis are presented in Figure 3.10 for the slow flow case and Figure 3.11 for the fast flow case.
Figure 3.10 – Change of various dryout-relevant metrics measured from the slow flow COMSOL model as the height of the ledge in the trench bottom is increased.

Figure 3.11 – Change of various dryout-relevant metrics measured from the fast flow COMSOL model as the height of the ledge in the trench bottom is increased.
First, it is worth noting that the most of the trends plotted above for the slow flow case terminate at a step size of 2.1 mm. At heights greater than 2.1 mm, the dryout minimum fully disappears, and the upwelling caused by the trench step just pushes downstream into the small initial downstream pileup. At this point, the ledge effect causes lithium to rise several millimeters above the initial level, so these heights are discounted. As expected, increasing the ledge in the bottom of the trench helps to decrease the minimum lithium level. By a height of 1.5 mm, the minimum is above the level of the 5 mm trench, meaning dryout would be avoided. One can also see that while the pileup slightly increases, the difference between the maximum and minimum lithium level continues to drop as ledge height increases. While the ledge effect pileup keeps increasing, for a 2.1 mm ledge the lithium height is still within 3 mm of the trench, which should provide good protection for the trenches in the high heat flux region without causing too much turbulence. After consideration of the trends, 1.8 mm seems to be an ideal height for the trench ledge. At this height, there is a very small difference between the maximum and minimum lithium levels at both time of minimum and time of maximum. The ledge and downstream pileups are limited, while ensuring the dryout minimum stays above the level of the trenches. In all of the cases, the recirculation zone or drain area should be expanded to account for inevitable lithium pileup. However, instead of being a single wave, the lithium level will be relatively sustained. To further illustrate the ledge effects, the series in Figure 3.12 shows the comparison between step sizes using the same time step for each of the tested ledge heights, up to 2.1 mm, and Figure 3.13 gives an example of how the flow develops in time for one of those ledge heights (1.8 mm).
Figure 3.12 – The same time step (1.2 seconds) presented for differing trench ledge heights, showing the mitigating effect trench shaping has on development of dryout. The color map shows flow velocity, and the dotted line marks the trench level/nominal lithium level.
Figure 3.13 – Frame-by-frame (every 0.5 seconds) of the best case for slow flow dryout mitigation using trench shaping. The color map shows flow velocity, and the dotted line marks the trench level/nominal lithium level.

For the fast flow case, the high velocity makes for a more turbulent scenario. High ledge effect lithium levels are unavoidable, but again, this helps to protect the trenches facing the largest heat fluxes. It takes at least a 2.4 mm step increase in the height of the bottom of the trench to fully counteract the effect of dryout. This is expected, since the higher heat flux and faster velocity should combine to create a stronger dryout scenario. In this fast flow case, the maximum pileup actually tends to decrease slightly as ledge height is increased. While the ledge effect lithium level keeps increasing, it does not adversely affect the drainage like the downstream pileup would, so it is decided that a ledge height of 2.7 to 3.0 mm would work for a high heat flux, high velocity case. These heights maximize dryout alleviation, and minimize downstream pileup.
3.5 Discussion and Application

The dryout concern mentioned above is more pressing for the typical tests of LiMIT flow. Testing in high heat flux environments such as the e-beam at UIUC, the divertor region in HT-7, or the linear plasma in Magnum-PSI has led to trench exposure as the lithium surface is depressed. Downstream pileup due the dryout formation and inadequate drainage for recirculation has also been observed. The model presented in Chapter 3 accurately depicts these experimental observations using the Moving Mesh module to model true free surface flow. The mesh can deform in response to the volume forces present, instead of staying locked in a rigid domain. While currently limited to a 2D slice of a trench system, the model still provides a valid engineering basis for further development of dryout mitigation strategies. Trench shaping can be directly implemented, as seen in the model extension in Chapter 3. Trench removal ideas can also be incorporated by adapting the rigid 3D models and importing volume force profiles to investigate how the free surface will react. Faster iteration of design proposals can be achieved in this way, and the solutions implemented will bring LiMIT closer to demonstrating full viability in fusion-relevant conditions.
CHAPTER 4 – WETTING ON NANOSTRUCTURED SURFACES

4.1 Background

As the use of liquid metals in plasma facing components becomes more widespread, it is important to investigate how those liquids interact with the surfaces onto which they are deposited. An important example of these interactions is the ability for liquid metals to wet fusion relevant substrates. Wetting is the ability of liquids to form interfaces with solid surfaces. The wettability, or degree of wetting, of a surface is defined by a force balance between adhesive and cohesive forces. When adhesive forces dominate, a droplet of liquid will spread out over a surface. In this case, the liquid is said to wet the surface, or the solid has good wettability. If the cohesive forces dominate, a droplet will appear to stay in a mostly spherical shape and not spread very far over the surface. This is the non-wetting case, and non-wetting liquids tend to have poor adhesion to a surface. The ability for a substance to wet a surface determines many important properties of a liquid-solid interaction, including the thickness of a liquid film and the propensity of a flowing liquid surface to break into rivulets.

A convenient measure of whether or not a liquid wets a surface is the contact angle. The contact angle for a liquid-solid interface is defined as the angle between the liquid-vapor and the liquid-solid interfaces. General convention defines the contact angle to be measured from the interface intersection point, with one ray pointing along the liquid-solid interface, and the other pointing along the liquid-vapor interface. Therefore, a liquid is said to wet the surface if the contact angle is less than 90°, and it does not wet if the contact angle is greater than 90°. The critical wetting point is at a contact angle of exactly 90°. This is illustrated in Figure 4.1.

![Diagram showing how contact angle relates to wetting of a liquid droplet on a solid substrate.](image)

**Figure 4.1** – Diagram showing how contact angle relates to wetting of a liquid droplet on a solid substrate.
While early ideas of contact angle and wettability can be traced back to Galileo\textsuperscript{[57]}, the generally regarded pioneer of surface wetting science is Thomas Young\textsuperscript{[58]}. For an ideal surface, Young’s equation is the result of the energy minimization problem between 3 phases when simplifying one phase to a flat, solid surface. This then yields

\[ \gamma_{SV} = \gamma_{LS} + \gamma_{LV} \cos(\theta) \]  

(4.1)

Here, \( \gamma_{SV} \) is the solid-vapor surface tension, \( \gamma_{LS} \) is the liquid-solid surface tension, \( \gamma_{LV} \) is the liquid-vapor surface tension, and \( \theta \) is the contact angle. In the case of these tests, the subscript \( V \) can also be taken to represent vacuum, as the testing chamber was evacuated. The graphic in Figure 4.2 labels these surface tensions.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{contact_angle_diagram.png}
\caption{The contact angle is determined by a force balance of the interfacial surface tensions.}
\end{figure}

Real surfaces are, unfortunately, never ideal. The most common departure from an ideal surface is simply surface roughness. When the solid surface deviates from a perfectly flat plane, the wetting characteristics of the surface will change. The Wenzel model\textsuperscript{[59]} proposes an adjustment to the contact angle to incorporate the presence of a roughened surface.

\[ \cos(\theta_W) = r \cos(\theta) \]  

(4.2)

The roughness ratio \( r \) is the ratio of the actual surface area of an interface to the geometric surface area, as measured along the plane of the interface. Since a rough surface will always have a greater actual surface area, the roughness ratio should always be greater than 1, and the apparent contact angle \( \theta_W \) will be greater than the true contact angle. This is shown in Figure 4.3.
When dealing with a heterogeneous surface roughness, the Wenzel model does not accurately describe the apparent contact angle. The Cassie-Baxter equation\cite{60} provides a better generalization of the Wenzel model. Cassie originally described the wetting case of a flat, chemically heterogeneous surface, and described the apparent contact angle $\theta_C$ as

$$\cos(\theta_C) = f_1 \cos(\theta_1) + f_2 \cos(\theta_2)$$ \hspace{1cm} (4.3)

Where $f_1$ and $f_2$ are the respective area fractions of each material, and $\theta_1$ and $\theta_2$ are the true contact angles on a pure sample of each surface. Cassie and Baxter together realized that if one of the materials was just vapor (or in this case vacuum), the theory could describe a simplified case of a roughened surface. The equation above then simplifies to

$$\cos(\theta_{CB}) = r_f f \cos(\theta) + f - 1$$ \hspace{1cm} (4.4)

In the above equation, $r_f$ is the roughness ratio of the wetted area and $f$ is the wetted fraction of the total surface area. The apparent contact angle $\theta_{CB}$ is again greater than the true contact angle, and it can be seen that the Cassie-Baxter equation simplifies to the Wenzel equation when $f = 1$ and $r_f = r$. Figure 4.4 shows the Cassie-Baxter contact angle.
It is pertinent to review some well-known cases of microstructures and nanostructures (and combinations thereof) that display enhanced hydrophobicity in nature. The two most common are known as the lotus effect and the petal effect, based off the leaf of the lotus flower and the petals of a rose. While superhydrophobicity in nature has been described in text for many centuries, it took until 1964 for the effect to be studied in detail [61], and several years after that for the development of the SEM to yield some insight into why some natural surfaces displayed hydrophobicity [62,63]. The terms “lotus effect” and “petal effect” came to describe 2 similar structures (depicted in Figure 4.5) in nature that exhibit interestingly different forms of hydrophobicity.

![Figure 4.5](image)

**Figure 4.5** – The structures seen on lotus leaves and rose petals lead to different conditions of non-wetting known as the lotus effect and petal effect.

The leaves of the lotus flower contain randomly spaced highly concave bumps (known as papillae) covered in tiny microfilaments [63]. The tight spacing and high concavity of these structures does not allow droplets or particle contamination to wet into the surface of the leaf, leading to the extreme hydrophobicity and self-cleaning properties of the lotus (as well as some other species). On the other hand, while droplets on a rose petal display very high contact angles (very little wetting), the droplets will not run off if the petal is tipped upside down (high adhesion), up to a point where gravity dominates the droplet’s surface tension. This is due to the slightly different structure that causes the petal effect [64]. The rose petal has a similar array of papillae covered in microfilaments and nanofolds in the surface, but the papillae are much less convex and the scale and spread is much larger. This allows a droplet to fill in between the papillae and maintain strong adhesion, but it will not be able to wet the smaller-scale microgrooves, resulting in a large contact angle.
4.2 Experimental Setup

4.2.1 Nanostructuring Apparatus and Sample Creation

The structured samples used for these tests were processed at Starfire Industries\textsuperscript{[65]}. An IMRA North America 10 Watt, 350 femtosecond near-infrared (1045 nm) laser was used, with a 1 MHz repetition rate. The structuring process was carried out at atmospheric pressure with ambient air or an inert gas shield. This is a suitable system for industrial processing, which can be easily adapted to process large areas. A diagram of the setup is presented in Figure 4.6, and pictures in Figure 4.7.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{setup_diagram.png}
\caption{Diagram of the laser structuring setup describing all components.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{setup_pictures.png}
\caption{Images of the laser, optical components, and the rotary stage setup for sample structuring.}
\end{figure}

Initial attempts entailed simple x-y translation of a stage containing square samples. This was a very slow process, and the small beam spot on the order of 10-30 µm caused micromachining, high oxidation, and ablation of the surface (see Figure 4.8).
Figure 4.8 – Simple x-y translation of the samples led to surface ablation and oxidation. This was not ideal, as clean, relatively uniform nanostructures were desired. Instead, circular coupons of stainless steel and molybdenum were placed on a rotary stage and rotated at high speed as x-translation was used to progress the beam radially outward. This allowed access to a sub-ablation regime where the non-linear laser interactions with the surface developed micro and nanostructures. Additionally, the beam spot was defocused to approximately 100 µm in order to decrease intensity and stay out of the ablation regime. Examples of the stainless steel and molybdenum samples, showing the processed annuli and bare metal regions in the center and along the edges, are shown in Figure 4.9. Processing time was heavily reduced utilizing the rotary stage, to approximately 1 minute per sample, meaning future structuring of large areas is definitely viable.

Figure 4.9 – Rotational motion coupled with x translation, along with slight defocusing of the laser beam produced uniform structured annuli and avoided surface ablation.

SEM images of the samples are shown in Figure 10a (stainless steel) and Figure 10b (molybdenum). In a majority of the structured areas, small grooves form on the order of 0.5-1 µm thickness. The beam is much larger than these features (100 µm) but the high power in the femtosecond pulses liquefies the surface and phonon/photon interactions create the patterning seen here. More study is needed to fully understand these effects.
On the molybdenum surface, the patterns seen are quite uniform, and actually resemble a semi-ideal Wenzel or Cassie-Baxter type of roughness structure. On the stainless steel, however, there is some slight radial variation in the structures that form. Larger structures begin forming on the order of 10 µm, which result in micro-scale structures with nano-scale patterning within. These structures look startlingly similar to those seen on the lotus leaf or rose petal, as discussed above. A direct comparison is given in Figure 4.11[64].

From the SEM images of the roughness, and especially the structures seen that mimic those in nature that cause superhydrophobicity, it was postulated that these nanostructured surfaces should impede wetting of liquid lithium. In order to find out, a series of contact angle tests must be performed.
4.2.2 Wetting Test Setup and Process

The Materials Characterization Test Stand (MCATS) chamber was used to carry out the wetting tests. The chamber is well suited to study wetting phenomena. The high vacuum, achieved via cryogenic pumping, allows for limited passivation of the lithium surface. In order to measure accurate contact angles, the lithium surface should be clean and free of any nitride or oxide. A lithium injector heats a reservoir of lithium and deposits controlled droplets onto samples beneath. Originally, the injector utilized argon backpressure to push lithium through the injector while maintaining an inert environment. This injector was used in previous wetting tests. While this is useful for larger volumes of lithium and larger substrate surfaces, it was found that droplet size was hard to control due to the required manual actuation of several valves to release pressure and stop the flow. Therefore, a manual injector was developed that held vacuum and allowed much finer control over droplet size using a ramrod that passed out of the chamber through an Ultra-Torr vacuum feedthrough. Droplets are injected onto a series of substrate samples (as seen in Figure 4.9) mounted on a stage. A stainless steel rod that passes through Ultra-Torr feedthroughs provides manual control of the stage. A plate heater mounted to the underside of the stage allows for testing wetting characteristics at high temperatures. The heaters for both the stage and the lithium injector are controlled by Variac variable AC transformers, and the temperature is tracked using Omega K-type thermocouples.

As in previous wetting tests, droplets were placed on the samples as the plate heater slowly increased the temperature. As the droplets are placed, temperature is recorded and a digital camera takes a picture of the droplet edge-on from the level of the sample coupon for later analysis. In order to avoid the phenomena of advancing and receding contact angles, the droplets fall from a non-zero height above the samples, allowing them to reach more of an equilibrium state. In this case, it has been seen that contact angle between the droplet and the wetted surface can stay “frozen”, especially since even at low base pressures, the temperatures involved incite fast passivation of the lithium surface. Therefore, in order to get larger data sets from one run of droplets, more lithium would be added to droplets already placed. Lithium was added quickly so as to break the frozen contact angle and form a fully new droplet with a new wetted area, and therefore a new equilibrium contact angle. A progression of this process is given in Figure 4.12.
Due to the method used, it is theorized that any deviation from equilibrium contact angle would be in the direction of the advancing contact angle. However, previous and current testing suggest that this effect is minimal, since the contact angles of expanded droplets at a specific temperature match the contacts of new droplets at the same temperature, to within experimental and measurement error.

The photos are analyzed using a previously developed MATLAB code\textsuperscript{[66]} that utilizes the MATLAB Image Processing Toolbox. The user manually marks the edge of the droplet and 2 lines, one along the solid substrate surface, and one along the interfacial edge of the droplet. Repeating the process multiple times yields a good average result, but user discrepancy and the manual placement introduces a contact angle error on the order of ±4°. Overall experimental error based on this process is about ±8°. As mentioned earlier, a droplet is said to wet if the contact angle is less than 90°, and not wet if it is greater than 90°. The transition between these 2 states, when the contact angle is exactly 90°, is called critical wetting, and this defines the wetting temperature of a liquid on a specific surface.

4.3 Review of Previous Results

In terms of liquid metal PFC’s, the main concern is the control of lithium flow and its interaction with solid substrates. For the LiMIT system, this is extended to include how well lithium will wet arrays of trench systems, since the trenches must be well filled for the TEMHD effect to drive flow. The surface tension of liquid lithium is quite high, 5 times that of water, which makes the study of its interaction with fusion relevant surfaces very important. It is this high surface tension that is responsible for keeping the lithium in the trenches of LiMIT once the
system is well wetted. However, this surface tension can also prove detrimental. In some cases, the wetting of some components is inhibited, while in others, preferential wetting causes wicking of lithium into undesirable areas. Both of these cases have been seen in previous tests of LiMIT systems, most notably on the vertical LiMIT tests. Here, the small size of the trenches (0.5 mm) in some cases inhibited wetting. Since the trenches were small compared to the injected lithium volume, the trenches could exhibit a Cassie-Baxter-like case of not wetting the trench “roughness”. In many of the tests on vertical LiMIT, stainless steel shim was placed along the edges of the trench structures to keep lithium from spilling over and out of the system in case of overfill. While they did their job, they also quite often preferentially wetted and wicked lithium up and out of the trenches.

Control of contact angles can be easily achieved using surface additives, like the natural epicuticular wax crystals that aid the lotus effect or any of a variety of chemical coatings that can make surfaces hydrophobic or hydrophilic. While these modifications usually deal with water or oil based liquids in atmosphere, this type of wetting control is not possible for fusion applications. In order to suppress impurities, any control of the wetting characteristics of a surface must be done without any additive chemicals. Additionally, the temperatures of these systems and the liquid metals involved would most likely not allow these solutions to be effective anyway. To this end, work has been done at CPMI to characterize lithium wetting characteristics on fusion relevant surfaces, and examine what surface modifications can adjust these wetting temperatures.

Fiflis et al. tested the wetting characteristics on various fusion relevant surfaces, including stainless steel, molybdenum, TZM, tungsten, and tantalum. This work defined the wetting temperature of liquid lithium on these materials with potential for use in fusion applications. It was shown that argon glow discharge cleaning for up to approximately 120 minutes proved effective at reducing the required wetting temperature of the solid surface. It was postulated that this was due to eradication of surface impurities and removal of the thin oxide layer. Additionally, pre-droplet coating of the surfaces with a thin layer of evaporated lithium drastically decreased the wetting temperature, down to the melting point of lithium in all cases. Since the materials in question in this work are stainless steel and molybdenum, the most
commonly used substrates for LiMIT, the previous results for those materials are shown in Figure 4.13.

**Figure 4.13** – Previous results, from [66], establishing the contact angle on unstructured stainless steel (a) and molybdenum (b) samples and showing plasma cleaning and lithium evaporation can drastically reduce the wetting temperature.

Further work has been carried out to describe lithium wetting on various lithium compounds [68]. It was shown that lithium wets lithium oxide and lithium nitride at a lower temperature than any of the fusion relevant surfaces studied by Fiflis, and that lithium carbonate wets better than a majority of them (W, Mo, Ta). It has also been discovered (Figure 4.14) that creating a mirror finish surface will allow immediate wetting of lithium at any point above the melting temperature [69].
Samples began as a mirror finish (28 nm roughness), and were gradually roughened manually. Typical roughness values for an unpolished sample would be on the order of micrometers. Until at least 160 nm average roughness, lithium readily wet the surface at any temperature above its melting point. Overall, these prior results have provided a good background in which to examine how the micro and nanostructuring of a surface affects wetting characteristics.

4.4 Wetting Tests on Structured Surfaces

Building off these previous results, this work conducted an investigation of how liquid lithium wets laser structured surfaces. To conduct the wetting tests, 4 samples were used concurrently, 2 molybdenum and 2 stainless steel. They were placed across the mobile stage and deposited on in succession. Multiple runs of wetting tests were needed to build up the results presented, since the structured regions of the samples were not large (on the order of an inch diameter). However, this repetition provided overlap in the temperatures tested, which verified the results and displayed repeatability in the transition from non-wetting to wetting regimes. Conveniently, the non-structured areas of the samples provided a means to simultaneously confirm past measurements of wetting temperature on bare metal surfaces. Sometimes, based on placement of the droplet or where it moved as the droplet size was increased, one of the droplet edges would come to rest on the non-structured center or extend past the structured region and impact the bare edge regions of the samples. Contact angle measurements from these cases
could be compared with the data from Fiflis et al.\cite{66}. It was previously reported that the wetting temperature of bare stainless steel is 315±1 °C; on bare molybdenum it is 324±1 °C. Figure 4.15 and Figure 4.16 show the new data taken from the bare regions of the samples overlaid on the previously measured data.

![Lithium Contact Angle on Stainless Steel](image1)

**Figure 4.15** – Contact angle measurements of lithium on the unstructured areas of the new stainless steel samples confirm past results of wetting temperature on bare, unstructured surfaces.

![Lithium Contact Angle on Molybdenum](image2)

**Figure 4.16** – Contact angle measurements of lithium on the unstructured areas of the new molybdenum samples confirm past results of wetting temperature on bare, unstructured surfaces.

On both substrates, the new data coincides nicely with the previously determined wetting temperature, verifying the past experiment and lending credence to the contact angle measurements on the structured regions.
Figure 4.17 – Contact angle measurements in structured regions of the stainless steel samples show an 83 °C increase in wetting temperature.

Figure 4.18 – Contact angle measurements in structured regions of the molybdenum samples show a 77 °C increase in wetting temperature.

Figure 4.17 and Figure 4.18 present the contact angle results for droplets on the micro and nanostructured areas of the samples. The wetting temperature is taken as an average between the last point that displays a non-wetting contact angle (> 90°), and the first point that displays wetting (< 90°). Using this method, the wetting temperature for lithium on nanostructured stainless steel is 398± 4°C, while lithium on nanostructured molybdenum is 401±4 °C. The micro-patterning of the surface increases the wetting temperature of stainless steel by 83 °C and molybdenum by 77 °C.

Previous results showed that both argon discharge removal of the oxide layer and other impurities\cite{68} and minimization of surface roughness\cite{69} could allow for substantial decrease in wetting temperature. In this case, both effects are likely at play. The increase in surface
roughness, especially due to the thin, trench-like structures, will induce a Cassie-Baxter state where the apparent contact angle is reduced due to the lithium not being able to wet into the regions between the trenches. The microscale structures seen on stainless steel that mirror those that cause the lotus and petal effects also undoubtedly play a geometric role in limiting wetting and increasing the contact angle. It is also postulated that the increased surface roughness allows for a tougher oxide layer to form on the surface. Since no argon discharge cleaning was carried out, this oxide layer, which is tougher for the liquid lithium to break down before wetting, aids in increasing the wetting temperature.

4.5 Correlation between Experimental and Theoretical Surface Roughness

It is hypothesized in this work that a large part of the significant increase in wetting temperature came as a result of the structuring of the surface. To that end, a theoretical examination of the relationship between the structure change and the wetting temperature was undertaken. As was briefly described earlier, while some of the structured surfaces appeared to have structures similar to what causes the lotus or petal effect (mainly on the stainless steel), the vast majority of the surfaces contained ordered rows of trenches. These looked quite similar to the surface in a Cassie-Baxter state (see Figure 4.4), meaning a wetted fraction could potentially be experimentally calculated.

Say there are 2 Cassie-Baxter-type surfaces. The apparent contact angle of a liquid on these surfaces would be

\[
\cos(\theta_{CB1}) = r_1 f_1 \cos(\theta_1) + f_1 - 1
\]  
\[
\cos(\theta_{CB2}) = r_2 f_2 \cos(\theta_2) + f_2 - 1
\]

In this case, there is one smooth surface and one structured surface. The smooth surface in the Cassie-Baxter theory will have a roughness ratio \( r_1 \) but the entire area will still be wetted, meaning the wetted fraction \( f_1 = 1 \). Therefore Eqn. 4.5 simplifies to

\[
\cos(\theta_{CB1}) = r_1 \cos(\theta_1)
\]
Using Eqn. 4.1 to substitute the true contact angle for a rearrangement of Young’s equation gives

\[
\cos(\theta_{CB1}) = r_f \left( \frac{\gamma_{SV1} - \gamma_{SL1}}{\gamma_{LV1}} \right) \tag{4.8}
\]

\[
\cos(\theta_{CB2}) = r_f f_2 \left( \frac{\gamma_{SV2} - \gamma_{SL2}}{\gamma_{LV2}} \right) + f_2 - 1 \tag{4.9}
\]

Now, at the wetting temperature, the apparent contact angle should be exactly 90°, meaning the left side of each of the above equations goes to 0. Therefore, the right sides can be set equal to each other, yielding

\[
\left( \frac{\gamma_{SV1} - \gamma_{SL1}}{\gamma_{LV1}} \right) = f_2 \left( \frac{\gamma_{SV2} - \gamma_{SL2}}{\gamma_{LV2}} \right) + f_2 - 1 \tag{4.10}
\]

In the above equation, the roughness ratio values were cancelled out. Since the effect is assumed to be caused by the microscale structures on the surface, it is assumed that the general roughness of the metal is still essentially equivalent.

It is well known that interfacial surface tensions vary with temperature. It has been shown\cite{70} that a good approximation is of the form

\[
\gamma = \gamma_0 \left( 1 - \frac{T}{T_{crit}} \right)^n \tag{4.11}
\]

Where \(\gamma_0\) is the surface energy at 0 degrees, and \(T_{crit}\) is the critical temperature where the surface energy goes to 0. The empirical parameter \(n\) can vary between 0.9 and 1.1, but is assumed to be 1 here. Plugging this fit into Eqn. 4.10 yields

\[
\left( \gamma_{SV0} \left( 1 - \frac{T_{wet,1}}{T_{crit,SV}} \right) - \gamma_{SL0} \left( 1 - \frac{T_{wet,1}}{T_{crit,SL}} \right) \right)
\left( \gamma_{LV0} \left( 1 - \frac{T_{wet,1}}{T_{crit,LV}} \right) \right)

= f_2 \left( \left[ \gamma_{SV0} \left( 1 - \frac{T_{wet,2}}{T_{crit,SV}} \right) - \gamma_{SL0} \left( 1 - \frac{T_{wet,2}}{T_{crit,SL}} \right) \right] + 1 \right) - 1 \tag{4.12}
\]
Where the surface tension subscripts stand for the solid-vacuum, solid-liquid, and liquid-vacuum interfaces. $T_{\text{wet,1}}$ and $T_{\text{wet,2}}$ are the wetting temperatures of the smooth and structured surfaces, respectively. This equation essentially provides a relationship between the wetted fraction of the structures and the wetting temperature increase seen on the structured surface. Fiflis et al.\cite{66} used initial wetting data taken to determine many of the $\gamma_0$ and $T_{\text{crit}}$ values for use in a different method used to fit the original flat surface contact angle data observed. In order to determine the $\gamma_0$ and $T_{\text{crit}}$ values for the solid-vacuum interface for stainless steel and molybdenum, literature data\cite{71,72} was fit to the relation in Eqn. 4.11. For the liquid-vacuum interface, $T_{\text{crit}}$ is the boiling point of lithium, and $\gamma_0$ is taken as the surface tension of liquid lithium near its melting point. The values for the solid liquid interface are derived by using the smooth surface contact angle relation at the wetting temperature, which gives

$$\gamma_{\text{SL}} = \gamma_{\text{SV}} \rightarrow \gamma_{\text{SL0}} = \frac{\gamma_{\text{SV0}} T_{\text{wet,1}}}{1 - \frac{T_{\text{wet,1}}}{T_{\text{crit,SL}}}}$$ (4.13)

This result was fit to the experimental data for the flat surface case to yield $\gamma_0$ and $T_{\text{crit}}$ for the solid-liquid interface. All of the required values are given in Table 4.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{\text{w1}}$</th>
<th>$T_{\text{w2}}$</th>
<th>$T_{\text{crit,LV}}$</th>
<th>$T_{\text{crit,SV}}$</th>
<th>$T_{\text{crit,SL}}$</th>
<th>$\gamma_{\text{LV0}}$</th>
<th>$\gamma_{\text{SV0}}$</th>
<th>$\gamma_{\text{SL0}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>315</td>
<td>398</td>
<td>1330</td>
<td>2225</td>
<td>1350</td>
<td>467.7</td>
<td>4450</td>
<td>4982</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>324</td>
<td>401</td>
<td>1330</td>
<td>2227</td>
<td>1600</td>
<td>467.7</td>
<td>6280</td>
<td>6728</td>
</tr>
</tbody>
</table>

After all of the necessary values are substituted into Eqn. 4.12, the wetted fraction of the structured surfaces can be derived, based on the difference in wetting temperature between the 2 surfaces. This yielded

$$f_2 = 0.70 \text{ for Stainless Steel}$$

$$f_2 = 0.75 \text{ for Molybdenum}$$
Next, the SEM images shown earlier in Figure 4.10 were imported into ImageJ, an image analysis software. To increase accuracy, a bicubic interpolation was used to increase the resolution of the images. The size was increased, and the distance across anywhere from 10 to 20 structures and trenches was measured in each image. In most cases, the data was taken linearly across the patch of surface that contained the most regularly ordered structuring. Experimentally, the wetted fraction is given by

\[ f = \frac{\text{distance across structure}}{\text{distance across structure} + \text{distance across trench}} \]  

(4.14)

The same amount of structures and trenches were measured in each sample image, the average width of both was found, and the wetted fraction was calculated. It is assumed that, as in the Cassie-Baxter diagram, no trenches are wetted, and the wetted area is restricted to the tops of the structures. The results of this process are shown in Figure 4.19 and Figure 4.20. Note that only 3 of the stainless steel samples were used here, as the large microstructures are not conducive to fractional area measurements.

![Figure 4.19](image_url)  

**Figure 4.19** – Experimental results of wetted fractional area for each of the stainless steel samples. The red point gives the overall average. The dotted line shows the theoretical prediction.
Figure 4.20 – Experimental results of wetted fractional area for each of the molybdenum samples. The red point gives the overall average. The dotted line shows the theoretical prediction.

In the figures, the error bars are the standard deviation in the measured wetted fraction, and it can be seen that the experimental results agree quite well with the theoretical values (dashed line in each plot). The red point represents the overall average in each case, 0.68 for molybdenum and 0.73 for stainless steel. While each case is well within measurement error, the slight undershoot for both materials is assumed to be from either other structures that allow slightly more wetting than the ordered trenches (like those seen in the stainless steel sample) or other non-uniformities which obviously exist. Overall, this shows that to the limit of being able to experimentally measure a fractional area of a structure, images of micro and nanostructures can be used to predict the wetting temperature of a material, or that a given increase in wetting temperature can yield insight into how structured a surface has become.

4.6 Discussion and Application

In this chapter, a laser structuring process was developed that was seen to induce micro and nanostructure formation on the surfaces of stainless steel and molybdenum. The drastic increase in wetting temperature observed on the structured surfaces paves the way for surface structuring techniques to be used to aid in flow control on metal surfaces. The approximately 80 °C gap provides a wide operating regime where structured surfaces will not readily wet and non-structured surfaces will wet without a problem. It is beneficial that this selective wetting regime occurs at the optimal operational temperature for liquid lithium in fusion devices, since lithium evaporation is still very low up to approximately 400 °C, where the structures begin to wet.
If the larger scale micro-structures can be more readily created and controlled, it may be possible to even more selectively control flow of liquid metals based on the difference between adhesion and wetting of a substrate, taking advantage of selective wetting in conjunction with the petal effect. Surfaces of divertor and limiter structures could be micro/nano-structured for flow control, effective thermal management, and prevention of material failure. This makes liquid metal divertor concepts more technologically feasible.

Additionally, the laser texturing process is rapid and easily scalable, allowing for efficient processing of large surface areas. This expands the applicability to larger first wall scale potential, as well as into other industries. Selective wetting of liquid metals based on temperature would be a valuable tool in many areas, including but not limited to electronics cooling, heat pipes, and turbine blades.
CHAPTER 5 – DESIGNS FOR LIMITER SYSTEM ON EAST

5.1 Background

The development of the LiMIT concept is progressing towards use as a fully general PFC: from divertors, to limiters, and even as a full first wall system. The next step is the fabrication and testing of a full scale LiMIT-based device for use in the Experimental Advanced Superconducting Tokamak (EAST) as a limiter. While more detail is given in the Introduction, it is pertinent to briefly reiterate previous tests of the LiMIT system, and how they relate to this large scale design.

LiMIT has shown promise as a liquid metal PFC in multiple tests at UIUC and elsewhere. Proof of concept testing at UIUC utilized an e-beam system impinging on a horizontal trench array to mimic a divertor heat flux stripe. While lithium dryout was exhibited in some of these tests, as a whole they proved that liquid lithium flow can be sustained using active cooling and a transverse magnetic field\textsuperscript{[37]}. The experimental conditions were expanded on horizontal LiMIT tests in HT-7 and Magnum-PSI, where heat fluxes up to 3 MW/m\textsuperscript{2} were handled effectively\textsuperscript{[40,43]}. Testing continued at UIUC with the small-scale vertical LiMIT device. The innovative chamber designed for testing allowed rotation of the LiMIT component while the cooling and magnetic fields were active. This yielded velocity measurements of sustained liquid lithium flow from horizontal up to 90°\textsuperscript{[39]}. The tests were taken further, and sustained lithium flow was observed at 180° from horizontal, with the open surface facing downward. No leaking or spilling of the lithium was observed for any tilted case, even in the areas of lithium overfill. The surface tension of lithium is high enough to prevent this while still allowing TEMHD flow to occur.

The EAST tokamak is the first experimental fusion device that uses superconducting magnets to create the poloidal and toroidal magnetic fields. It was built as an upgrade to the HT-7 tokamak and is a pioneer in long pulse tokamak operation, reaching a record continuous run time of 102 seconds for a shot in early 2016. General parameters are given in Table 5.1\textsuperscript{[73]}, along with some parameters relevant to this limiter design.
The MAPES transfer arm on the device allows for diagnostics or material test surfaces to be inserted into the device during a run campaign. It features an exchange box and load lock, with a limiting 50 cm diameter port leading into the device. This allows for the insertion of experimental devices into the main vacuum chamber as outer limiters. The transfer arm reaches the plasma slightly above the midplane, meaning the main face of the EAST limiter design will be tilted to 13.5° past vertical. A diagram of this is shown in Figure 5.1.

![Diagram of the EAST chamber, including the MAPES transfer arm that can be used to insert an external limiter.](image)

**Figure 5.1** – Cross section of the EAST chamber, including the MAPES transfer arm that can be used to insert an external limiter.

A notable previous test of a free surface liquid lithium flow system on EAST is of the Flowing Liquid Lithium (FLiLi) device[^74]. Developed at Princeton Plasma Physics Lab, the FLiLi concept proposes having a thin film of liquid lithium flow over a heat sink to act as a PFC. Lithium is fed into a distributor nozzle filled with miniscule holes, and it is designed to let lithium slowly flow down a guide plate through the area of plasma impact. While not intended

### Table 5.1 – Parameters of the EAST Device and the External Limiter

<table>
<thead>
<tr>
<th>EAST Parameters</th>
<th>Device</th>
<th>Limiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field</td>
<td>3.5 T</td>
<td>Size</td>
</tr>
<tr>
<td>Plasma Current</td>
<td>0.5 MA</td>
<td>Trench Width</td>
</tr>
<tr>
<td>Major Radius</td>
<td>1.7 m</td>
<td>Placement</td>
</tr>
<tr>
<td>Minor Radius</td>
<td>0.4 m</td>
<td>Cooling (air or He)</td>
</tr>
<tr>
<td>Plasma Center</td>
<td>1.8 m</td>
<td>Angle</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>1-1000 s</td>
<td></td>
</tr>
<tr>
<td>Parallel Q</td>
<td>9 MW/m²</td>
<td></td>
</tr>
<tr>
<td>Perpendicular Q</td>
<td>0.5 MW/m²</td>
<td></td>
</tr>
</tbody>
</table>
to be used in high heat flux divertor regions, the FLiLi device was tested on both HT-7 and EAST as a limiter. In both cases, imperfect wetting and potential blockage of the distributor channels impeded the development of a uniform lithium film\cite{50,75}. Instead, lithium would coalesce into rivulets much like water running on a pane of glass. The LiMIT design presented here seeks to improve upon previous LiMIT experiments and incorporate lessons learned from the FLiLi tests, in order to create a fully self-contained and effective large-scale flowing liquid lithium system.

5.2 Design

The design shown here is the result of an ongoing collaboration with the EAST team in Hefei. Throughout the iterative design process and discussions with the EAST team, several potential issues and ideas were brought to light. The designs presented here are the compiled results of this process. A labeled, all-encompassing schematic is shown in Figure 5.2 to act as a reference as each subsystem is explained in the following sections. The design consists of a main trench piece with cooling tubes running through its center, a backing plate and heater plate, a bottom reservoir for lithium replenishment and filling, a DC electromagnetic pump system for filling, and an upper reservoir for lithium distribution.
5.2.1 Trench Flow

The trench piece of the EAST limiter is shown in Figure 5.3. Based off of the difficulties seen in wetting the 0.5 mm trenches in the vertical LiMIT tests, as well as the size of the full-scale device, the trench size will be increased to 2 mm. This size has been tested in the horizontal LiMIT experiments, and will enhance wetting and decrease resistance to filling due to lithium surface tension. The larger size will also alleviate the risk of clogs and debris buildup, providing cleaner lithium flow.
The trench structures will continue along the front and back of the trench piece, helping to confine lithium and to maintain a constant thin film. On the top of the trench piece, the open channels continue, in order to allow for distributed filling and continuous TEMHD circulation. On the front surface facing plasma impingement, the TEMHD driving force will accelerate the lithium flow down the surface and into the reservoir. This aids in increasing the heat flux removal and lowering the maximum lithium temperature.

As seen in Table 5.1, it is expected that the first wall or the limiter will experience a maximum heat flux on the order of 0.4-0.6 MW/m². This is well within the tested range of previous LiMIT devices. In order to investigate the flow characteristics in the EAST trenches, previous 3D LiMIT models were adjusted and simulated in COMSOL Multiphysics.

![Image of trench domain](image.png)

**Figure 5.4** – COMSOL trench domain used to model flow in the EAST limiter trenches.

The domain, shown in Figure 5.4, describes the heat flux profile used and also marks gravity, which was included as a body force with components based on the angle from vertical of the trench. While it is presented horizontally, keep in mind that the open face of the trench will be tilted to 13.5 degrees past vertical. As in Chapter 2, the model relies on the coupling between the Electric Currents, Heat Transfer in Fluids, and Laminar Flow modules. The plasma heat flux is imposed on the top surface, while the bottom surface provides a heat flux from the heaters. For simplicity and computational constraints, the domain does not include a reservoir. Therefore, the model will ultimately slightly overestimate the total flow velocity and the lithium temperature, since there is no interaction with the reservoir to effect slowing or cooling of the flow.
The open surface heat flux is taken from early discussions about the possibility of placing LiMIT in EAST. At that time a 15 cm high coupon was planned, and it was assumed the entire surface would be heated. Therefore, a 0.5 MW/m² heat flux was imposed along the middle 15 cm of the trench, assuming placement in EAST is similar and the current design just extends the top and bottom. When introducing a stark edge of the heat flux, COMSOL has trouble dealing with the boundary regions. Therefore, in order to avoid solver divergence that can occur when there are abrupt changes in heat flux, a wide Gaussian was used that provided at least 0.5 MW/m² over the middle 15 cm of the device. This also more accurately depicts how the heat flux should impact the flat plate as it is inserted into the plasma. A heat flux of 0.2 MW/m² is used for the entire bottom surface, in order to include the heater plate. Initial temperature is 200 °C, which is an optimal initial operating temperature, though it is likely it will start higher in experimental tests. The magnetic field magnitude is 1.0 T, since the device will be placed on the edge, where the magnetic field drops from the nominal 3.5 T. Here, a steady state solution is presented, which should result if EAST is run with a LiMIT limiter for 10s to 100s of seconds. It is seen that the profile deviates slightly from the usual smooth high velocity region extending from the high heat flux. This is due to both the extended heat flux over the majority of the domain increasing velocity more uniformly, as well as the cooling channels providing slightly higher local cooling in some regions that will drive faster flow. The cooling channel effect is usually not observed in short timescale models, and it is pronounced here in this long term steady state solution. The topside open surface exhibits an average velocity of approximately 25 cm/s, meaning the lithium will be subjected to the heat flux for approximately 1 second before reaching the reservoir. The stable velocity profile is shown in Figure 5.5.
The steady state temperature profile is quite smooth. While the maximum temperature reaches 655 °C, stays between about 250 °C and 350 °C. This is shown in Figure 5.6.

Figure 5.5 – Steady state velocity profile in an extended LiMIT trench. Color map shows velocity in m/s.

Figure 5.6 – Steady state temperature profile in an extended LiMIT trench. Color map gives temperature in Kelvin.
This result is quite encouraging, as it suggests that the lithium temperature can remain quite low even in long pulse operation, outside of the high evaporation regime that begins around 400-450 °C. While the initial operation temperature may be above 200 °C, the low level of increase is key. Additionally, this model does not include a reservoir for remixing and cooling of the lithium coming off of the hot open surface, and therefore should overestimate the ultimate lithium temperature.

Due to the velocity of the lithium flow and the acceleration it experiences on the way down the front surface, there is a possibility of lithium dryout, as seen in Chapter 3. Those results suggest trench shaping over the bottom half of the trench piece can alleviate this problem. However, the extent of the dryout should be lessened due to the more gradual flow acceleration exhibited here. In an e-beam or divertor heat flux stripe, a sudden, high-intensity heat flux drives large acceleration, but the slower increase in flow speed here may allow the film or the filling system to correct the issue. This will have to be investigated in further large scale system testing.

5.2.2 Heating and Cooling

In order to fill the device, the trench array and reservoir must be heated. Effective wetting via gravity and capillary action will take place if the trenches are at approximately 350 °C (assuming no other surface modification has been performed). To this end, a heater plate is attached to the trench backing plate as seen in Figure 5.7, and a plate heater will be attached to the reservoir.

Figure 5.7 – Top side view of the LiMIT limiter, showing the back side heater plate.
This backside heater plate contains an array of cartridge heaters that can provide an even 0.2 MW/m$^2$ to heat the trenches and allow lithium to fill and wet well. Additionally, steady state liquid lithium flow should be achievable before insertion into the plasma. The heater plate provides the temperature gradient necessary to drive lithium flow from the backside trenches, similar to the vertical tests done at UIUC with no open surface heat flux. The cartridge heaters will be linked to temperature controllers via an array of thermocouples in order to ensure even heating.

For effective vertical TEMHD-driven flow, the thermoelectric driving force must be able to counter both the flow-retardant MHD forces and the body force from gravity. It has been shown that since the lithium viscosity is low, the effect from MHD drag in the trenches is negligible$^{[37]}$. In order to show how the TEMHD force can overcome gravity, Eqn. 2.16 from Chapter 2 is used. From here, it is assumed the flow is at a standstill, meaning the rising pressure gradient term is equal to the thermal gradient term.

\[
\frac{1 + C \frac{\partial P}{\partial z}}{\sigma B^2} = \frac{S - S_w}{B} \frac{dT}{dy}
\]  

(5.1)

Solving for the pressure gradient yields

\[
\nabla P_z = \frac{\sigma B (S - S_w)}{1 + C} \nabla T_y
\]  

(5.2)

Where in this case z is the vertical direction and y is into/out of the trenches. In order to drive flow, the pressure gradient must be larger than the gravitational body force $\rho g$.

\[
\nabla P_z > \rho g \rightarrow \frac{\sigma B (S - S_w)}{1 + C} \nabla T_y > \rho g
\]  

(5.3)

Therefore, rearranging the above equation yields a minimum temperature gradient required to drive flow against gravity using the TEMHD effect.

\[
\nabla T_y > \frac{\rho g (1 + C)}{\sigma B (S - S_w)}
\]  

(5.4)
At the nominal magnetic field in EAST of 3.5 T, this results in a temperature gradient of greater than 45 K/m. At edge magnetic field values of 0.5 to 1.0 T, this requirement increases to 440 and 220 K/m, respectively. This seems relatively trivial, considering the temperature gradients achieved in previous tests of the LiMIT system at UIUC reached 2665 K/m\textsuperscript{[39]}. However, the size of the device must be considered. The entire length of the snaking cooling lines in the horizontal LiMIT device is equal to merely 2 lengths of the 30x30 cm EAST design module. So while previous COMSOL trench flow models assumed that the cooling lines could all be taken at room temperature, this may not be the case for the LiMIT flow in EAST.

Therefore, simulations of the cooling lines were carried out using the Heat Transfer in Solids (HTS) and Non-Isothermal Pipe Flow (PF) modules in COMSOL Multiphysics. The PF module allows lines drawn on work planes through a 3D geometry to be treated as a pipe with a 2D cross section, rather than attempting to create weaving extrusions through a material. The user inputs the temperature and inlet and outlet conditions, and the PF module couples with the HTS module to show how heat from the bulk is transferred into the cooling lines. Initial cooling line geometries were based on the snaking design used in prior LiMIT tests. The initial line velocity was set to 30 m/s with a volumetric flow rate of 40 liters/min, equivalent to testing at UIUC. This was assumed as a conservative case based on current capabilities, instead of expecting specific future developments in the cooling methods used. As will be done in EAST, helium is used as the cooling gas. The block is solid stainless steel, besides the implied cooling lines from the PF module. This simplified geometry is used as a conservative test case to determine if the cooling lines will be able to sustain an even heat flux to drive TEMHD flow. In the real scenario, the trenches will eliminate some material, the lithium will carry away heat from the bulk, and the plasma heat flux will give much larger temperature gradients. In the first several geometries, the cooling lines very quickly reach the ambient temperature of the bulk. This slightly cools the top, but leaves the majority of the block hot until the top portion starts to cool down.

This realization and further testing led to the final design, which consists of single pass cooling lines that alternate in flow direction. In the center, the cooling line temperatures are all similar, so this arrangement allows for hot outlets to be interspersed with cool inlets, evening out
the temperature distributions along the edges as well. Figure 5.8 shows an example of the temperature distribution of the bulk.

![Temperature profile in a stainless steel slab, after being cooled for 60 seconds by alternating single pass cooling lines.](image1)

**Figure 5.8** – Temperature profile in a stainless steel slab, after being cooled for 60 seconds by alternating single pass cooling lines.

The important parameter, though, is the temperature gradient. Figure 5.9 shows a close-up of the bulk with an inlay slice depicting the temperature gradient in the y direction, into the trenches.

![Close view of the temperature profile in the limiter size slab. The color maps show temperature in Kelvin (right side heat map) and temperature gradient (left side rainbow color map).](image2)

**Figure 5.9** – Close view of the temperature profile in the limiter size slab. The color maps show temperature in Kelvin (right side heat map) and temperature gradient (left side rainbow color map).
Obviously, the gradient is very high, which should mean there will be no problem providing the desired temperature gradient. Figure 5.10 confirms this, by limiting the color map to the highest case mentioned above, ±440 K/m, to show that a sufficient thermal gradient persists throughout the bulk, as opposed to being concentrated around the cooling lines.

![Figure 5.10 – Close view of the temperature profile in the limiter size slab. In this case, the color map for the temperature gradient is limited to ±440 °C to show high temperature gradients exist through to the outer edges of the slab.](image)

The addition of trench structures and lithium should work to increase the temperature gradients seen, since lithium has a better thermal conductivity than stainless steel, and the trenches will act as fins in the liquid flow. Therefore, the results above show a limiting case that should be improved upon by the real physical system. These tests result in the cooling lines shown protruding from the device in Figure 5.11. While this may seem unwieldy, it actually eliminates the need for machining the snaking cooling line grooves and the inclusion of end caps over said grooves. Cooling line inlets and outlets can also be promptly coalesced into a smaller number of larger lines to pass out of the EAST vacuum chamber.
5.2.3 Reservoirs, Injection, and Filling

This design includes a dual reservoir system. The lower reservoir is a tested system that works with infrastructure already installed on EAST. As seen in Figure 5.12, the trenches extend deep into the reservoir, eliminating possibility of spilling or leaking.

The bulk lithium in the reservoir (over 1 liter) will be able to resupply any lithium lost by evaporation or sputtering while running, allowing for longer operation times. It also provides a heat exchange function for the hot lithium coming from the front surface, keeping the overall
temperature lower. The top reservoir shown in Figure 5.13 is included to eliminate the clogging and distribution problems seen in the EAST FLiLi test.

Figure 5.13 – CAD drawing of the upper reservoir and distributor branches of the filling system.

The closed reservoir allows for safe pooling of the lithium and the ability to provide some slight backpressure, which will aid in filling and distribution through the channels. As mentioned earlier, the TEMHD trenches continue along the backside and top of the trench piece, so the upper reservoir also permits continuous TEMHD circulation while providing any required refilling.

For the large EAST design, original ideas called for filling by aid of the capillary force. Capillary action, also known as wicking, of a liquid is the result of the surface tension and adhesive forces between the liquid and container walls acting to propel the liquid up through a narrow channel. Assuming the conservative case of a fully vertical surface and a perfectly wetting liquid, the height a liquid column can reach under capillary action alone is given by

$$h = \frac{2\gamma}{\rho gr}$$

Where $\gamma$ is the liquid-vapor surface tension, $\rho$ is the liquid density, $g$ is the gravitational constant, and $r$ is the radius of the tube. The parameters used and the unassisted wicking height for several trench diameters are given in Table 5.2. After the decision was made to increase the trench diameter, it became clear that external filling would be necessary.
Table 5.2 – Examples of Capillary Wicking for Different Trench Widths

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Trench Width (r)</th>
<th>Wicking Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>0.405 N/m</td>
<td>0.5 mm</td>
<td>32 cm</td>
</tr>
<tr>
<td>ρ</td>
<td>515.52 kg/m³</td>
<td>1.0 mm</td>
<td>16 cm</td>
</tr>
<tr>
<td>g</td>
<td>9.8 m/s²</td>
<td>1.5 mm</td>
<td>10 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 mm</td>
<td>8 cm</td>
</tr>
</tbody>
</table>

The back-pressured needle based filling methods used on both horizontal and vertical LiMIT designs would require too much precision and additional infrastructure in EAST. Therefore, a well-tested technology that has previously been used on EAST will be utilized: a DC electromagnetic (EM) pump.

An EM pump takes advantage of the same J x B Lorentz force that the TEMHD effect uses, though an EM pump requires an externally driven rather than a thermoelectric current. In this case, a tube passing out of the bottom of the lower reservoir will pass through 2 copper electrodes providing the driving current. This is shown in Figure 5.14.

![Figure 5.14 – CAD drawings of the DC EM pump.](image-url)
To determine the necessary driving current and voltage, a pressure drop analysis is once again employed. From Miyazaki et al.\cite{76}, the MHD pressure drop through a pipe is shown to be

\[
\Delta P_{MHD} = L \frac{c_w}{1 + c_w} \sigma_f u B_0^2 \quad \text{with} \quad c_w = \frac{\sigma_w (r_o^2 - r_i^2)}{\sigma_f (r_o^2 + r_i^2)}
\]  

(5.6)

All of the variables, along with their values are given in Table 5.3. Note the subscripts w and f stand for wall and fluid, respectively, throughout.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_0)</td>
<td>3.5 T</td>
</tr>
<tr>
<td>(u)</td>
<td>2 cm/s</td>
</tr>
<tr>
<td>(\sigma_w)</td>
<td>1.35x10^6 (Ω-m)^{-1}</td>
</tr>
<tr>
<td>(\sigma_f)</td>
<td>3.3x10^6 (Ω-m)^{-1}</td>
</tr>
<tr>
<td>(R_i)</td>
<td>5 mm</td>
</tr>
<tr>
<td>(R_o)</td>
<td>5.5 mm</td>
</tr>
<tr>
<td>(L)</td>
<td>0.75 m</td>
</tr>
<tr>
<td>(w)</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

This calculation assumes a conservative 0.75 meters for the piping length, to account for extra length provided by the 3-fold distributor seen above in Figure 5.13. This distributor aids in dispersing the lithium flow as it enters the top reservoir to further alleviate selective filling concerns. To protect against any additional pressure drop from the splitting of the pipe, the branches will be tapered with respect to the main feed line to maintain uniform velocity throughout. The velocity is set at 2 cm/s to present a case with ample flow. The current drive can be lowered to relax the pumping when necessary, allowing for flow control during operation. The parameters above (using the conservative nominal B field) give an MHD pressure drop of 22689 Pascal, which must be provided by the Lorentz force created via the driving current and the toroidal magnetic field in EAST.

\[
\Delta P_{MHD} = \Delta P_{\times B} = \frac{I_{EM}B}{2r_i}
\]  

(5.7)
Where $I_{EM}$ is the electromagnetic driving current, which comes out to 64.8 Amps. To determine the voltage drop across the terminals, both simple $V = IR$ and the MHD voltage drop are considered.

$$V = HuB + IR = HuB + I \frac{H}{2r_i L_{EM} \sigma_f}$$

Where $H$ is the height between the 2 terminals and $L_{EM}$ is the length of the tubing that is actively pumped. For an estimated 2 cm $L_{EM}$, the voltage drop is $1.85 \times 10^{-3}$ volts. From here, the current in the walls can be determined.

$$I_w = \frac{V}{R_w} = V \frac{\sigma_w 2(r_o - r_i)L_{EM}}{H}$$

Which gives a total of 4.54 Amps through the walls of the tubing. This is a small percentage of the total driving current, and should not adversely impact operation. A high current, low voltage power supply can easily provide ample flow for filling and resupplying lithium to the trenches.

5.3 Preparation and Operation

The full system (refer back to Figure 5.2) will be installed on EAST, taking advantage of existing infrastructure to minimize unnecessary development on both ends. Figure 5.15 shows the system mounted on the transfer arm and installed in the exchange box.

![Figure 5.15](image_url) – The LiMIT limiter for EAST mocked up on the transfer arm (a) and inside the transfer box (b).
The lower reservoir includes a loading hole to accommodate the LIPES lithium injection system already installed on the MAPES exchange box in EAST. This system is diagramed in Figure 5.16.

![Diagram of LIPES lithium injection system in place on EAST](image)

**Figure 5.16** – The LIPES lithium injection system in place on EAST, which will be used for reservoir filling.

Once the system is mounted on the transfer arm in the exchange box, the exchange box will be evacuated and the LiMIT module will be heated to approximately 350 °C. Lithium in the LIPES reservoir and feed pipe is melted and loaded into the lower reservoir. While still at temperature, the EM pump will fill the top reservoir and provide backpressure if required to fill the trenches. Once properly wetted, the temperature of the device is lowered to below 300 °C, the transfer arm is extended, and the full scale LiMIT module can begin operation as a limiter on the EAST tokamak.

5.4 Discussion and Application

The analysis and design presented in this chapter form the basis of development of a LiMIT module to be installed on the EAST tokamak as a limiter. As in much of this work, the models developed for trench flow and cooling provide a method of increasing the efficiency of the design process by allowing ideas to be tested theoretically before physical implementation.

The LiMIT system placed on EAST hopes to demonstrate further viability of TEMHD-driven flowing liquid lithium in a fusion environment. The inclusion of lithium in fusion devices has presented many benefits to plasma performance, including higher confinement, ELM pacing or elimination and reduced impurity content (see Chapter 1 for elaboration). The inclusion of a
flowing, constantly refreshing film eliminates the problem of lithium evaporation and improves heat flux removal from the PFC surface, and testing in EAST’s long pulse discharges will truly test all components. Proving the capabilities of a contained LiMIT system (especially the reservoir and pumping system abilities to resupply lithium quickly and effectively) in this environment will provide a good first step toward development of a full lithium loop, which will be able to pump lithium out of the system after plasma impingement, filter and degas it, and pass it back into the device, all during long-pulse operation.
CHAPTER 6 – CONCLUSION AND FUTURE WORK

As prospects for fusion power inch toward reality and progress is made on development of ITER, the struggles lie increasingly in the areas of PMI and PFC advancement. Without more knowledge of how the plasma and the wall interact and influence each other, and invention of novel concepts to handle the extremely high intensity conditions in these future devices, the evolution of fusion power production will be stalled once again. This thesis focuses on methods of improving the reliability of one of those concepts – the LiMIT flowing liquid lithium PFC. While the device has been tested at UIUC and in several devices around the world, it will benefit from enhanced flow control to improve reliability. The project includes both COMSOL Multiphysics simulations and experimental work to tackle several key issues seen in liquid metal PFCs.

The proof-of-concept LiMIT system developed in Chapter 2 proved compact flow in novel geometries is possible. The development of eddies and turbulent circulation and the velocities in these regions matched model predictions, while sustained lithium flow was observed through the most shallow trench areas. According to model extensions, this system should be able to sustain TEMHD-driven flow on the order of 60 cm/s when impacted with stronger heating systems, increasing the heat transfer capabilities and providing new methods of controlling lithium flow characteristics.

The stretch goal extension of this high flow system application requires handling heat fluxes on the order of 100 kW/cm², equivalent to 1 GW/m². This heat flux will be brought in the form of intense beam heating. The next step is developing methods for lithium cleaning and impurity filtering, so lithium flow at high heat flux is not hindered in any way by scaling or passivation. If flow is interrupted, component damage could result. After that is brought online, high heat flux testing can commence. Based on the results of wetting experiments, both presented and referenced in Chapter 4, there are plans to utilize methods for conditioning and surface treatment to enhance flow and wetting in the trench regions, and hinder wetting and spilling where flow is not desired.

At times, the high heat flux impingement on lithium-filled trenches causes high local acceleration that drives depression of the lithium surface known as dryout. This could lead to
critical failure of the device in fusion-relevant conditions. The models in Chapter 3 simulate the dryout phenomenon and reproduce features seen in experimental observation, including both upstream and downstream pileup as the slower lithium flow interacts with the locally high velocities. The moving mesh allows the simulation to capture true behavior of the free lithium surface. The models investigate methods of mitigating dryout, and the most effective solution found is increasing the height of the trench bottom slightly past the highest heat flux region of the trench. For a 5 mm trench with 1 cm/s background velocity, a step increase of 1.8 mm maintains a lithium level above the 5 mm height of the trenches, alleviating dryout, and the pileup caused as a result of the ledge obstructing flow provides extra protection for the trenches in the highest heat flux region. As the flow speed increases, higher ledge heights are needed to counteract dryout. For a 10 cm/s flow, 2.7 to 3.0 mm is effective. The model can be adjusted further to account for specific system needs and geometries, and inform trench shaping solutions.

Concerns exist that the ramp system presented in Chapter 2 will exhibit lithium dryout, exposing solid surfaces to the high intensity conditions. Since the trenches are generally reduced or eliminated in the high velocity region, this will not be a significant problem. The nozzle effect induced by the ramp is also effective for reducing dryout concerns, funneling a large volume of lithium through the center region at high speed. This is in effect the trench shaping mechanism of dryout mitigation informed by the work in Chapter 3, where the trench bottom is adjusted to account for the depression of the lithium surface. Furthermore, eventual operation of the system inverts the orientation of the trench module, submerging the trenches in liquid lithium. It is this reasoning, as well as computational constraints, that led to the rigid surface model being used for the simulations presented. While further study will be required to determine how this affects development of dryout, it will likely have an alleviating effect.

While the 2D dryout model does provide investigative potential into mitigation strategies, future work will attempt to extend the model to full 3-dimensional implementation. To accomplish this goal, issues with the solid-liquid interface conditions must be addressed. Alternative methods and software could provide better handling of the complex coupled physics along with the interaction between fluids and solid structures. Ansys Fluent is a prime candidate, as it is optimized for multiphase and open surface fluid flows. Gerris Flow Solver is an open source software designed for complex multiphase problems. It employs automatic adaptive
mesh refinement techniques and precise surface tension models to accurately solve complex multiphase systems. It is even possible that fully Lagrangian solvers can be used for this system, though the accuracy in small systems over relatively short timescales must be heavily researched. Better diagnostic preparation coupled with further testing of dryout solutions will also allow stronger quantitative analyses of dryout parameters for refinement of the models. Information from these tests will be used to update future versions of dryout models, which will be able to predict more than the transient conditions, and instead provide information on steady state flow based on the geometries tested.

Liquid metal PFC designs, especially LiMIT, heavily rely on the wetting properties of the liquid on the solid materials used as base structures. Chapter 4 provides evidence that laser micro and nanostructuring of stainless steel and molybdenum surfaces has the ability to drastically increase the wetting temperatures of liquid lithium. Stainless steel showed an increase of 83 °C, while molybdenum’s wetting temperature increased by 77 °C. When used in conjunction with the surface polishing techniques previously studied, these methods provide an operating regime from essentially the melting point of liquid lithium all the way to 400 °C where selective wetting can be achieved and flow can be dictated by structuring the surface. The rapid laser texturing process provides possibilities for large-scale surface structuring for increased application in fusion devices.

The sum total of the work done to investigate the wetting properties of lithium and other liquid metals on different substrates has yielded a substantial number of methods to control when wetting occurs. Future wetting tests plan to continue to higher substrate temperatures while limiting evaporation to provide a better picture of how these control methods influence liquid metal behavior. Study of other important liquid metals like tin or tin-lithium eutectics can also be achieved at higher temperatures (in the tests done in this work, tin bounced off the surface of the substrates, displaying a highly non-wetting condition). Future work now must also include detailed investigations of flow properties on structured materials. This entails fabrication of patterns meant to exhibit guided liquid metal flow, and testing of more relevant systems instead of simple structured samples. Continued study of the laser structuring process is also important in order to understand the mechanisms behind the micro and nanostructure formation and to see
if said structure formation can be controlled based on system parameters like frequency, intensity, number of beam passes, or processing speed.

The design process continues to bring the design of a LiMIT-based limiter for EAST to fruition, as seen in Chapter 5. Further studies of flow conditions are warranted, to coincide with testing of trench systems. It is recommended that the development of this system progress in a step-by-step basis, testing each component and adjusting designs before combining and testing the entire system. The most uncertain aspect of the design as it stands is the EM pump filling of the trenches. Ample distribution and even wetting is key for effective system operation, so investigation into optimizing the pumping and filling design is important. It is also important to investigate, via a combination of modeling and experiment, how the thickness of lithium film changes over the front surface. If the lithium overfill in the trenches is too large, there may be a thickening of lithium levels toward the bottom of the trenches, since the constraining effects of surface tension are strongest only within the trenches. As all components are tested and certified operational, a full model will be tested in the HIDRA device at UIUC. This device will act as a test bed for new component ideas before they are brought to large-scale fusion systems, so it is a perfect place to test the EAST design to work out the kinks before operation in EAST.

Additional studies will focus on the retention abilities of liquid lithium. A low recycling wall is beneficial for tokamak operation as the plasma core is kept warmer and more stable, and more free of impurities. While lithium is known as a very efficient impurity getter, it also has a high affinity for hydrogen and its isotopes. If large liquid lithium PFCs are eventually shown to getter almost everything that impinges them, developing the technology to filter the lithium and recover the deuterium and tritium sponged out of the system is critical. This must be something that can be done quickly during device operation, or large tokamaks will shortly run out of fuel as it all diffuses to the edge and disappears into the liquid PFCs. Studies are already underway to investigate this hydrogen retention problem, and will continue with hydrogen recovery investigations.

Ultimately, these chapters provide methods that when used in conjunction can increase the effectiveness and applicability of liquid lithium PFCs. Flow velocity governance, dryout risk mitigation, and surface structuring can provide enhanced flow control and guidance of the
lithium, while increasing thermal management, preventing the risk of damage to solid materials, and minimizing lithium creep and spilling. The models developed serve as a testbed for future iterations of system concepts, streamlining the design process and making it more efficient. All of these techniques can come together to enhance the viability of large scale liquid lithium PFC systems. This will lead to exciting possibilities for future testing in large scale fusion devices, reaching ever forward to the goal of sustainable fusion power.
REFERENCES


[69] Sandoval, C. Private Communication.