HEAT TRANSFER ANALYSIS OF THERMOELECTRIC DRIVEN SWIRLING FLOW

BY

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THESIS

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Abstract

As fusion experimental devices progress it has become a challenging problem to remove the intensive heat from the divertor region. The solid plasma facing materials (PFM) suffer from the sputtering and thermal stress. An alternative way is to utilize liquid metal especially the liquid lithium as the divertor material. An experiment on CDX-U found that a shallow pool of liquid lithium could bear 60MW/m² heat flux without significant evaporation. A swirling flow pattern was observed during the experiment which was firstly believed to be Marangoni effect. To reveal the truth of this flow the Solid/Liquid Lithium Divertor Experiment (SLiDE) was constructed at University of Illinois, Center for Plasma-Material Interactions. SLiDE has similar experimental conditions as CDX-U and in recent experiments thermoelectric magnetohydrodynamics (TEMHD) was proved to be the dominant driven force of this kind of swirling flow. Its fluid properties were fully investigated later and a group of equations have been developed to describe the velocity field.

Following the previous work this thesis focuses on the heat transfer analysis of the TEMHD driven swirling flow. An infrared (IR) camera system was installed and calibrated to monitor the surface temperature change under different experimental conditions especially the highly focused heat flux. In addition the 3D dimensionless heat transfer equation is analyzed and simplified for experiment related parameters. A relevant 3D convection heat transfer model was built to calculate the detailed temperature distribution and the results were compared to the IR camera results. Good agreement was achieved under some conditions while some difference generated when the height of the liquid lithium was changed. The changing velocity field in the boundary layer was raised as a possible reason.
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Chapter 1 Introduction

1.1 Plasma-wall interactions and plasma facing materials
In fusion research, plasma-wall interactions have always been a major topic [1]. Although the extremely hot plasma is confined by a magnetic field in the tokamak the plasma is not really detached from the vacuum wall. In fact, many types of plasma-wall interactions happen and the plasma facing surface suffers from high energetic particle bombardment, radiation and the accompanying high heat flux, which lead to backscattering, outgassing, sputtering and evaporation of wall material. These interactions may release impurities into the plasma edge. Some of the impurity particles will diffuse back to the core plasma and the high temperature plasma will lose a lot of energy through impurity’s Bremsstrahlung radiation, excitation and ionization [2]. In addition, these interactions may cause severely recycling problems to provide extra deuterium close to the wall. The edge plasma density will be out of control and the plasma temperature will be lowered through inelastic collision.

It is very important to control the recycling and suppress the impurity density in the tokamak. One way is to attach a limiter to the inner surface of vacuum vessel. The limiter is usually a solid block that extrudes into the magnetic field lines. Because in the tokamak charged particles mainly travel along the magnetic field lines and magnetic field lines are parallel to the wall the limiter can block the field lines close to the wall surface and create a so-called scrap-off layer (SOL) between the major plasma and the wall surface. In this way, the size of the core plasma is confined and the diffusion length from the wall to the core plasma is greatly increased. In addition, when energetic particles from disruption or other instability effects come out the limiter will be the first part to suffer the bombardment which protects the inner wall from being damaged.

These days, many tokamaks actually use the divertor to control the edge plasma. Unlike the limiter’s magnetic field configuration, the idea of the divertor is to form open magnetic field lines close to the wall and conduct all these lines to enter the divertor target plate surface. When charged particles enter the open field lines they will travel along these lines and hit the target surface before diffusing back to the core plasma. With the divertor, the shape of the magnetic field lines can be actively controlled so that the plasma edge is well determined. Usually the
divertor target is far away from the core plasma and extra localized pumping systems are sometimes installed near the target plate to pump the neutral particles formed on the target surface out of the chamber. This cannot be achieved by limiter and has become the main method to remove the He ash (one type of fusion products) from tokamak chamber.

Figure 1.1 Left is the Mo limiter of FTU tokamak and right is the divertor sketch for ITER tokamak.

No matter whether a limiter or a divertor is used, a big problem is how to deal with the incoming heat flux and energetic particles flux. Strong plasma material interactions (PMI) always happen on the surface of the limiter or the divertor target plate. Generally speaking it is convenient to choose tungsten (W) or molybdenum (Mo) as the limiter or divertor material due to their low sputtering yield, resistance to erosion, high heat conductivity and high melting point [3]. However these types of materials are high-Z materials and because the Bremsstrahlung radiation is proportional to $Z^2$ a small amount of high-Z material existing inside core plasma will cause a huge amount of energy lost. Needless to say their strong line radiation and high energy cost of ionization. On the other hand some low-Z material such as graphite, ATJ graphite, Carbon-Fiber-Composite (CFC) [4] and beryllium (Be) [5] are also good choices. However the erosion problem by chemical sputtering on graphite is severe and its tritium retention also prevents the graphite’s utilization in future tokamaks. Actually choosing the right type of material for the ITER divertor is still under discussion in spite of the previous plan to use W and ATJ graphite [3]. For beryllium although it has low sputtering yield and hydrogen isotopes retention it is very poisonous and expensive for large scale application [6].
Some important technologies are raised to improve the divertor. One is to increase the gas density close to the divertor target plate which is called gas-puff [7]. In this way the radiation is increased before the divertor target so that the direct deposit energy is lowered. Another one is called snowflake divertor [8]. The snowflake divertor utilizes the second-order null of the poloidal field to create snowflake shape field lines before the divertor target plate. In this way the flux-expansion near the X-point is enlarged and the connection length to the target becomes longer.

However there is no doubt that the high heat and particle flux become harder and harder to handle with the increasing plasma parameters. Although ITER is planning to use solid material as its divertor surface the expected heat flux (~10MW/m²) [9] is already very high for solid material. Once the divertor surface is permanently damaged it may take a lot of time and money to repair with inner robot technology, especially after tritium is used in ITER. In the mean while the divertor design is always a complex structure and formed by difference layers of material attached to each other. Once the high temperature gradient appears and disappears for many times the thermal stress due to different expansion rate may cause potential failure of the divertor tile leaving the inner part exposed to the high temperature plasma.

1.2 Recent liquid lithium research

An alternative way is using liquid material as plasma facing components (PFC) material. Candidates include lithium (Li), Sn-Li eutectic, molten salt (Flibe), gallium (Ga) and etc. [10], among which Li has drawn most of the interest from the fusion community in these days. As a choice for PFC components, liquid lithium has a lot of advantages. First of all, the PFC surface is no longer susceptible to damage or transient events inside fusion reactors. Even if some part of the surface is evaporated it will recover in short time. Second, liquid lithium has a strong heat removal capability due to convection heat transfer. In addition as a type of reactive material the liquid lithium can easily getter impurity particles and pump hydrogen isotopes to lower the recycling and improve the plasma performance [11]. This ability may also be utilized to pump tritium out of the chamber.
A series of experiments on CDX-U used different sizes of free surface liquid lithium trays as the limiter and showed significant improvement of the plasma performance, which include the electron temperature increase, the greatly suppressed recycling and the impurity reduction. A main discovery is that the plasma loop voltage is lowered by a factor of 4 which means the plasma resistance is much smaller [12]. Similar experiments were done on HT-7 with a movable free surface liquid lithium tray as a limiter and reveal a similar result [13]. The hydrogen recycling decreased by a factor of 4 based on the H-alpha line intensity and the particle confinement time increased by a factor of 2. In addition the lithium tray was moved inside the tokamak and the H-alpha measurement array only showed a strong intensity decrease where the tray was placed.

A crucial disadvantage of using this kind of free surface liquid lithium tray directly as the PFC is that the free surface liquid lithium under the strong heat flux and magnetic field may cause unexpected MHD effects. The Divertor Material Evaluation Studies (DiMES) project reported that large volume of liquid lithium ejected into the plasma during the normal discharge which led to plasma disruption [14]. The ejection of small liquid lithium droplets was also observed on CDX-U [12] and HT-7 [13]. Some simulations of the ejection on DiMES suggested shorting out the current moving perpendicular to the field to avoid the ejection [15] and on CDX-U no significant ejection was discovered after the tray was carefully grounded which forced the current entering the tray to flow along the toloidal field [16]. But since the magnetic field strength on CDX-U is not as big as large tokamak it is hard to say if this works for all tokamaks.

Another way to minimize the ejection problem is changing the liquid lithium limiter to capillary porous system (CPS) configuration [17]. In CPS configuration the liquid lithium surface is covered with a layer of porous stainless steel mesh and because of the capillary pumping by the mesh the liquid lithium will eventually form a thin layer above the stainless steel mesh appearing like a free surface. T-11M developed CPS as a liquid lithium limiter technic and realized a 0.3s quasi steady state tokamak regime and clean deuterium plasma with its $Z_{\text{eff}}$ is almost 1. No lithium ejection was detected even during abnormal plasma events such as disruptions, ELMs and runaways [18]. Similar results were also achieved on FTU with a similar CPS configuration [19].
An important liquid lithium PFC was the new liquid lithium divertor (LLD) installed in NSTX [20]. This LLD consists of a thin porous Mo layer sprayed by plasma on top of a thin stainless steel layer with a copper heat sink attached to the back side. Liquid lithium was evaporated and deposited onto the LLD surface until the target thickness of liquid lithium was reached. On NSTX ELM was strongly suppressed after a large amount of liquid lithium was coated on LLD and nearby ATJ graphite tiles [21]. Detailed analysis proves that the density profile control of the plasma is the key to the ELM suppression [22].

1.3 Thermoelectric magnetohydrodynamics

The motionless liquid lithium PFC is not the ultimate solution for fusion since the impurity and hydrogen isotopes will eventually saturate and by then the lithium has to be replaced. Furthermore, the liquid lithium PFC is slowly eroded by the incoming energetic particle flux and the erosion speed has a positive correlation with the lithium surface temperature [23]. What is more, liquid lithium is vaporized when heated by the plasma and since its saturated vapor pressure rises exponentially with the surface temperature it becomes crucial to control the surface temperature in case that the pressure at the edge is too high for the tokamak. However the surface temperature of liquid lithium is harder to control with an increasing heat flux on the PFC surface these days.

As a result flowing liquid lithium surface seems to be a better choice for the plasma facing surface inside the tokamak. Many ideas have been proposed such as fast flowing lithium film over the divertor surface and free surface lithium jet [24] while most of them met with MHD problems due to the enormous magnetic field strength in tokamak.

In 1979, Shercliff suggested that since thermoelectric current generates when a temperature gradient exists inside the liquid lithium, it can be driven by Lorentz force if a strong magnetic field is placed perpendicular to the current, which is called thermoelectric magnetohydrodynamic (TEMHD) driven flow [25]. Many experiments reveal the existence of the TEMHD flow and this becomes an important phenomenon for crystal growth [26] and alloy solidification [27] when the magnetic field is used to mitigate the convection.
Although this suggestion was originally made for the lithium flow in the blanket it may also work for liquid lithium PFCs because of the steep temperature profile near the plasma heating area. With specific design liquid lithium can be driven by the magnetic field to flow over plasma striking region, which can effectively remove the heat from the direct heating area and maintain the plasma facing surface fresh while the surface temperature is under control.

During an open tray liquid lithium test on CDX-U the liquid lithium swirled under a 60MW/m$^2$ heat flux from a narrow electron beam (e-beam) and no significant evaporation was observed, which was explained as Marangoni effect when the result was reported [29]. In University of Illinois a project called Solid/Liquid Lithium Divertor Experiment (SLiDE) was built to investigate this result and Jaworski succeeded to prove that this kind of swirling is caused by the TEMHD effect and demonstrated that both the magnetic field and the temperature gradient can be used to control the flow [30][31]. Jaworski developed a model to estimate the swirling velocity based on the interface temperature distribution measured between the liquid lithium and its stainless steel container. The estimated velocity actually matches the swirling velocity measured by tracking the movement of small impurity particles on top surface.
The above CDX-U results and SLiDE results initiate the research to use the TEMHD driven liquid lithium flow as the PFC surface. To use the TEMHD driven liquid lithium flow as the PFC the temperature distribution in the fusion relevant environment is undetermined yet. It is important to note that the temperature, especially the surface temperature, of liquid lithium PFC is crucial to the hydrogen isotopes retention, erosion, lithium evaporation, edge plasma density control and heat removal. The purpose of this work is to estimate the temperature distribution of this flow based on the known velocity and the measured thermal boundary conditions. The top surface temperature distribution will be measured by an IR camera and compared to the calculation result. In addition, the depth of the liquid lithium and the bottom material with different Seebeck coefficients will be taken into consideration.
Chapter 2 SLiDE facilities

2.1 Experiment setup

SLiDE project is designed to investigate the liquid lithium flow in the environment that is similar to the divertor region, which includes the high heat flux that is up to 10MW/m$^2$ and a strong magnetic field. Figure 2.1 describes the SLiDE experiment setup and figure 2.2 is the 3D view of the setup, in which the directions of the coordinate system are defined and this definition will be used in the whole thesis. Lithium is contained in a squared stainless steel tray and melted by a Gaussian shape linear electron beam which is installed to mimic the heat flux at the divertor region. The direction of the electron beam is normal to the surface of the lithium. A Helmholtz coil is used to focus the beam and in the meanwhile provides a magnetic field normal to the lithium tray. The lithium tray is attached to a sandwich shape multi-layer steel plate which has 14 pairs of embedded thermocouples to measure the temperature at the interface between the lithium and the tray. On the other side of the thermocouple plate a copper heat sink is attached to absorb the heat. The lithium surface can be observed through the top window with the help of a mirror next to the electron gun. Either a digital camera or an IR camera can be installed on top of the chamber to measure the flowing velocity or surface temperature of the lithium surface. The whole chamber is kept under vacuum during experiments.
Figure 2.1 SLiDE experiment setup

Figure 2.2 SLiDE experiment setup in 3D view
2.2 Vacuum system and lithium preparation

Lithium related experiments are always challenging because lithium reacts with many types of gases such as nitrogen, oxygen, carbon dioxide and water vapor quickly and easily. If a lithium chunk is exposed to air directly its silver surface becomes dark in a few seconds and this process can be accelerated if the air is humid. If fresh lithium is left inside the vacuum only maintained by a rough pump it will become dark in days. Worse still, when lithium is heated to a high temperature or melted the reaction rate becomes faster.

The vacuum system of SLiDE consists a turbo pump (Pfeiffer 1080), a rough pump and a few gauges. The base pressure is usually kept at around $5 \times 10^{-7}$ Torr. During experiments the gauges directly connected to the main chamber will be shut off in case they are damaged by the lithium vapor. The turbo is intentionally installed far away from the main chamber but still we can find some oxidized lithium powder inside the pipe in front of the turbo.

Loading lithium into the tray includes three steps. First, a glove box is filled with Argon (Ar) gas and a certain amount of solid lithium will be cut inside. Both Sand paper and file are used to clean the lithium surface until it appears silver. Second, the whole chamber is pumped to vacuum and then filled with Ar gas. Note that in both steps the Ar pressure needs to be a little bit larger than the atmosphere pressure to keep the air away. Third, small fresh lithium pieces are sealed in a plastic bag inside the glove box and loaded into the tray quickly.

2.3 Magnetic field

The magnetic field is generated by a pair of Helmholtz coils and it was measured by a Gauss meter and scaled to the current inside the coil which can be measured instantaneously by the high current DC power supply. Because that the uniformity of the standard Helmholtz coil is beyond the second order of the field gradient the field around the liquid lithium can be assumed uniform in the experiment. The relation between the field and the coil current is

$$B \ [Gauss] = -2.2 + 6.8 * I_{coil} \ [A]$$

(2.1)
2.4 Electron beam

The electron gun is installed right above the tray. The electrons are accelerated by a high voltage power supply of which the voltage is 10 kV and the current is up to 1 A. The electron gun can generate a Gaussian shape electron beam with the other direction be linear. The beam profile is shown in figure 2.4. The e-beam relies on the magnetic field to focus. The length of the beam is $L_{beam}$ on y direction and the distribution on x direction is a Gaussian profile with the standard deviation $a_0$. The current density of the electron beam is

$$J = \begin{cases} 
    j_0 \times Exp\left(-\frac{x^2}{a_0^2}\right) & \text{when } |y| \leq L_{beam}/2 \\
    0 & \text{when } |y| > L_{beam}/2 
\end{cases} \quad (2.2)$$

Because the beam needs the magnetic field to focus the values of $L_{beam}$ and $a_0$ are actually determined by the magnetic field and they are summarized in table 2.1.
Figure 2.4 Electron beam profile on the tray surface. Gaussian distribution on x direction and linear on y direction

Table 2.1 Electron beam profile summary [30]

<table>
<thead>
<tr>
<th>Magnet current [A]</th>
<th>$a_0$ [mm]</th>
<th>Beam length $L_{beam}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>44.2</td>
<td>82</td>
</tr>
<tr>
<td>5</td>
<td>29.2</td>
<td>87</td>
</tr>
<tr>
<td>10</td>
<td>12.5</td>
<td>77</td>
</tr>
<tr>
<td>20</td>
<td>6.7</td>
<td>70</td>
</tr>
<tr>
<td>40</td>
<td>4.6</td>
<td>65</td>
</tr>
<tr>
<td>60</td>
<td>4.7</td>
<td>69</td>
</tr>
<tr>
<td>80</td>
<td>3.8</td>
<td>70</td>
</tr>
<tr>
<td>100</td>
<td>3.6</td>
<td>69</td>
</tr>
</tbody>
</table>

In equation (2.2) $J_0$ is the solution of the equation

$$J_0 = \frac{I_{beam}}{L_{beam} \int^{L_{tray}/2}_{-L_{tray}/2} \exp \left(-\frac{x^2}{a_0^2}\right) dx}$$  

In above equations $L_{tray}$ is the length of the lithium tray which is 10 cm. $x$ is the position on the lithium surface. $I_{beam}$ is the total current emitted by the electron gun and it can be read directly from the high voltage power supply.
Since the energy of the electrons from the electron beam is 10keV the stop range of the electrons in the lithium can be found on National Institute of Standards and Technology (NIST) website. The average stop range of 10keV electrons in the lithium is 1.4µm. So during the experiment when the electrons hit the lithium surface all of their kinetic energy is assumed to deposit onto the surface of the liquid lithium. The Bremsstrahlung radiation at the surface is neglected here because the Bremsstrahlung radiation becomes important only when the energy of the electrons is larger than 0.511 MeV. Under the above assumptions the heat flux profile \( q \) is

\[
q = V \cdot J = \begin{cases} 
V \cdot J_0 \cdot \text{Exp} \left( -\frac{x^2}{a_0^2} \right) & \text{when } |y| \leq L_{\text{beam}}/2 \\
0 & \text{when } |y| > L_{\text{beam}}/2 
\end{cases}
\]

(2.4)

Here \( V \) is the voltage of the acceleration power supply which is set to be 10 kV in the experiment. A 3D view of the heat flux is plotted in figure 2.5.

![Figure 2.5 Surface heat flux created by the electron beam (when the magnet current=60A)](image)
2.5 Tray system

![Diagram of the SLiDE tray system]

The tray system (figure 2.6) includes a stainless steel tray (figure 2.7), a thermocouple array (figure 2.9) and a copper heat sink (figure 2.8). The liquid lithium is contained in a 10cm by 10cm square shape stainless steel (SS) tray with a 2mm thick round bottom plate whose diameter is 14cm. The depth of the tray is about 3cm but usually less than 2cm liquid lithium is injected into the tray. Under the stainless steel tray, there are two separate SS plates with 14 pairs of thermocouples embedded and attached with heat transfer cement (figure 2.9). These thermocouples were stainless steel sheathed thermocouple from OMEGA and the model number is KMQSS. The diameter of the thermocouple is 1mm. The thickness of the thermocouple plate is 1.5mm and the diameter is also 14cm. A 1.5mm stainless steel plate with the same diameter is placed between two thermocouple plates to separate them. A copper heat sink is attached to the backside to cool down the whole system.
Figure 2.7 The picture of the stainless steel tray

Figure 2.8 Thermocouple array and cooling system

Figure 2.9 Pictures of the thermocouple array and how the thermocouples are embedded in the stainless steel plate
Figure 2.10 Thermocouple pair to measure local heat flux (Left) and thermocouple array with 14 pairs of thermocouples to measure temperature distribution at the interface between lithium and tray (Right)

During the experiment when the lithium is heated above 200°C the temperature of the copper heat sink is still lower than 100°C and this generates a large temperature difference over the SS plates. In the thermocouple array a pair of thermocouples is embedded vertically. Since the thickness of the stainless steel plate is much smaller than its diameter, the heat flux on the vertical direction should be much larger than the horizontal heat flux. Most of the heat must transfer vertically and it can be measured by the vertically placed thermocouples (figure 2.10). The temperature difference can be read directly from the thermocouples. However the distance between the thermocouples is not determined yet. The diameter of the thermocouple tip is about 1mm and the thermocouples are attached with some heat transfer cement. Also the thermal contact between each plate is not perfect. As a result it is not appropriate to directly measure the physical distance between thermocouples. A uniform heat flux on the top surface was generated by a heater and the temperature values of all the thermocouples were recorded. If the temperature difference between the vertically placed thermocouples is divided by the given heat flux it gives the effective distance \( d_1 \) between both thermocouples. The effective distances for all the thermocouples are listed in table (2.2).
When the distance $d_1$ between both thermocouples is known the local heat flux can be calculated. In addition if the distance from the interface to the upper thermocouple $d_2$ is known the temperature of the interface $T_{\text{interface}}$ can also be calculated if we assume that the vertical heat flux does not change:

$$T_{\text{interface}} = T_2 + \frac{d_2}{d_1} (T_2 - T_1)$$ (2.5)

Table 2.2 Calibration of the effective distance of each thermocouple pair for interface temperature measurement [30]

<table>
<thead>
<tr>
<th>Thermocouple pair</th>
<th>Thermocouple position[cm]</th>
<th>d1[mm]</th>
<th>d2[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0,0)</td>
<td>4.025 ±0.086</td>
<td>2.95 ±0.3</td>
</tr>
<tr>
<td>2</td>
<td>(0,-1)</td>
<td>2.848 ±0.061</td>
<td>2.96 ±0.3</td>
</tr>
<tr>
<td>3</td>
<td>(0,2)</td>
<td>3.049 ±0.099</td>
<td>2.75 ±0.28</td>
</tr>
<tr>
<td>4</td>
<td>(0,-3)</td>
<td>1.684 ±0.049</td>
<td>2.89 ±0.29</td>
</tr>
<tr>
<td>5</td>
<td>(0,4)</td>
<td>3.655 ±0.113</td>
<td>2.22 ±0.22</td>
</tr>
<tr>
<td>6</td>
<td>(0,5)</td>
<td>2.893 ±0.078</td>
<td>2.15 ±0.22</td>
</tr>
<tr>
<td>7</td>
<td>(0,-5)</td>
<td>3.306 ±0.078</td>
<td>2.35 ±0.24</td>
</tr>
<tr>
<td>8</td>
<td>(-2.5,0)</td>
<td>3.270 ±0.069</td>
<td>3.13 ±0.31</td>
</tr>
<tr>
<td>9</td>
<td>(2.5,0)</td>
<td>4.147 ±0.118</td>
<td>2.36 ±0.24</td>
</tr>
<tr>
<td>10</td>
<td>(1,-3)</td>
<td>3.472 ±0.099</td>
<td>2.53 ±0.25</td>
</tr>
<tr>
<td>11</td>
<td>(-2,-3)</td>
<td>2.183 ±0.045</td>
<td>3.09 ±0.31</td>
</tr>
<tr>
<td>12</td>
<td>(3,-3)</td>
<td>4.653 ±0.087</td>
<td>2.18 ±0.22</td>
</tr>
<tr>
<td>13</td>
<td>(5,-3)</td>
<td>4.523 ±0.086</td>
<td>2.14 ±0.21</td>
</tr>
<tr>
<td>14</td>
<td>(-4,-3)</td>
<td>2.955 ±0.052</td>
<td>3.2 ±0.32</td>
</tr>
</tbody>
</table>
2.6 IR camera

2.6.1 IR theory and mechanism of IR camera

Infrared radiation (IR) is the light with the wavelength between 750nm and 1mm. Any object whose temperature is higher than 0K has thermal emission. If the surface of a certain object can absorb all radiation hitting its surface we can say it is a black body. Its thermal emission spectrum can be described by Planck’s law.

\[ B_\lambda(T, \lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_BT}} - 1} \]  

(2.6)

Here \( B_\lambda(T) \) is the spectral radiance and its unit is W/m^3. \( h \) is Planck constant. \( c \) is the speed of light in vacuum. \( k_B \) is the Boltzmann constant. \( T \) is the surface temperature.

The energy that a black body emits per unit time through a unit area can be achieved by integration of Planck’s law.

\[ I_{emission} = \int_0^{\infty} B_\lambda(T, \lambda) d\lambda = \int_0^{\infty} \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_BT}} - 1} d\lambda = \sigma T^4 \]  

(2.7)

Here \( \sigma \) is Stefan-Boltzmann constant which is 5.67*10^{-8} W/m^2K^4.

However the real material emission always has a fraction which is called emissivity \( \varepsilon \). Theoretically the emissivity is a function of surface temperature, wavelength, emission angle and thickness. If the surface of the object cannot absorb all the radiation, some part of the radiation will be reflected. The surface reflectivity \( r \) is the fraction that the radiation is reflected. Also some times the object is not opaque and some of radiation can transmit with a fraction of \( \tau \). A relation between these three fraction is \( \tau + \varepsilon + r = 1 \). Normally if the object is opaque the reflectivity \( r = 1 - \varepsilon \).

If the emission from the object is measured the surface temperature of the object can be derived. The mechanism of IR camera is to measure the thermal emission. However IR camera only measures the thermal radiation within a certain spectrum region and this is the filter range of the IR camera \( (\lambda_1 \sim \lambda_2) \).
Usually if the object is not transparent and the emissivity does not change too much for the spectrum span of the IR camera it is safe to assume that the emissivity is only a function of temperature. This is called gray body assumption and under this assumption the equation can be changed to

\[ I_{\text{emission}}(T) = \int_{\lambda_1}^{\lambda_2} \varepsilon B_\lambda(T, \lambda) \, d\lambda = \varepsilon(T) \int_{\lambda_1}^{\lambda_2} \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{k_B T}{\lambda}} - 1} \, d\lambda \]  

(2.9)

And this integration can be solved numerically so that the emission intensity is only a function of temperature. The intensity is measured by the detector and calibrated to the temperature with the help of a unique object having an emissivity very close to 1. This forms the calibration file for the IR camera which translates the relative measurement of the intensity to a temperature value.

However in real measurement we have to consider the infrared light from the background since the object surface reflectivity is not zero which means that there exists some infrared light that is reflected by the object surface and enters the IR camera.

\[ I_{\text{measure}} = I_{\text{emission}} + I_{\text{reflection}} = \varepsilon(T) \int_{\lambda_1}^{\lambda_2} \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{k_B T}{\lambda}} - 1} \, d\lambda + \left(1 - \varepsilon(T)\right) \int_{\lambda_1}^{\lambda_2} \frac{1}{e^{\frac{k_B T_{\text{background}}}{\lambda}} - 1} \, d\lambda \]  

(2.10)

For the IR camera since the relative intensity measurement corresponds to the temperature we can have

\[ I_{\text{real}} = \int_{\lambda_1}^{\lambda_2} \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{k_B T}{\lambda}} - 1} \, d\lambda \]  

(2.11)

and

\[ I_{\text{background}} = \int_{\lambda_1}^{\lambda_2} \frac{1}{e^{\frac{k_B T_{\text{background}}}{\lambda}} - 1} \, d\lambda \]  

(2.12)

Now
\[ I_{\text{measure}} = \varepsilon(T) \cdot I_{\text{real}} + (1 - \varepsilon(T)) \cdot I_{\text{background}} \quad (2.13) \]

and the real surface temperature can be measured if the emissivity is known.

2.6.2 IR camera setup on SLiDE and data collection

The IR system on SLiDE includes an IR camera (Inframetrics 760), a view port, the framework to hold the camera, a PCI digital card (DT3152-LS) to communicate with the IR camera and a computer to record data and install control software (SandIR from Sandia National Lab).

![SLiDE IR setup diagram](image)

Figure 2.11 SLiDE IR setup

The main parameters of the IR camera Inframetrics 760 are summarized here. All related information can be found in its manual. The detector is made by Mercury/Cadmium/Telluride (HgCdTe) and runs at 77K. Each time before the camera starts it takes about half an hour to cool down the detector. The camera has three spectral band pass including 8~12μm, 3~5μm or 3~12μm. Usually only 8~12μm is used in experiments. The resolution is 1.8mRad which corresponds to distance/1000 approximately. Temperature measurement accuracy is ±2°C or ±2%. Field of view (FOV) is 15 degree (vertical) * 20 degree (horizontal) and it has 4 times continuously adjustable electric-optic zoom. The temperature measurement range is -20°C to 400°C with a normal filter when emissivity is set to 1 [33].
To hold the camera on top of the chamber an adjustable frame made with aluminum bars was designed and installed (figure 2.12). The inclined angle can be easily adjusted and the whole frame can move horizontally with no problem. Because normal glass window has poor transmission rate for IR a Zinc Selenide (ZnSe) window is installed as the view port for IR camera.

The IR image is recorded by a desktop computer which has a PCI digital card to communicate with the IR controller. The signal from the controller is 8-bit and an IR camera program called SandIR (from Sandia National Lab) is used to read the signal and rebuild the image on the computer screen. In the software a certain emissivity map can be built and assigned to the image so that the software can instantaneously display IR images corrected with the user-defined
emissivity map. The IR image can be saved as an Origin matrix file and the temperature value of each pixel is recorded.
Chapter 3 Experimental operation, analysis and results

For the experiments in this work, a chunk of lithium is placed in the steel tray and melted by the e-beam. The e-beam heating generates the thermoelectric (TE) current within the liquid lithium. The magnetic field which is vertical to the lithium surface interacts with this TE current and results in a Lorentz force in the angular direction to drive the liquid lithium to swirl. Heating power, magnetic field and liquid lithium thickness can affect the swirl velocity and its heat transfer.

![Image](Figure 3.1 The photo image (top view) of the swirling liquid lithium surface.)

Figure 3.1 is the photo image of the swirling liquid lithium surface. The center part is the shiny liquid lithium surface which can only reflect the dark background inside the vacuum chamber and some part of the electron beam filament instead of diffusely reflecting the light everywhere.

Figure 3.2 is the cross sectional view of the liquid lithium and the tray describing how the liquid lithium swirls. Since the center is heated by the e-beam the temperature gradient is mostly along the radial direction generating the thermoelectric current [25] in the same direction. The magnetic field vector is vertical to the surface of the liquid lithium so there is an angle between the magnetic field vector and the current direction. The Lorentz force is generated on both side of the incoming heat flux. On the left side the direction of the Lorentz force is into the page and on the right side the direction of the Lorentz force is out of the page. The liquid lithium swirls under this driven force and the direction is labeled by the blue arrow.
In this experiment the heat transfer leads to an uneven temperature distribution which generates thermoelectric current and affects the driven force of the flow. On the other hand this driven force changes the flow field which in turn affects the heat transfer. The heat transfer and the momentum transfer are actually coupled hence the MHD effect cannot be neglected. To find out the velocity and temperature distribution in this incompressible swirling flow problem we need to solve continuity equation, Navier-Stokes equation, heat transfer equation and Ohm equation.

\[ \nabla \cdot \vec{u} = 0 \quad (3.1) \]

\[ \rho \left( \frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla P + \mu \nabla^2 \vec{u} + \vec{j} \times \vec{B} \quad (3.2) \]

\[ \rho c_p \left( \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot \left( k \nabla T - ST \vec{j} \right) + \Pi + \frac{\vec{j} \cdot \vec{j}}{\sigma} \quad (3.3) \]

\[ \vec{j} = \sigma \left( -\nabla \varphi + \vec{u} \times \vec{B} - ST \nabla T \right) \& \nabla \cdot \vec{j} = 0 \quad (3.4) \]

Here \( \vec{u} \) is the velocity of the fluid. \( \rho \) is the density of liquid lithium which is 508.8 kg/m\(^3\). \( \mu \) is the dynamic viscosity of the liquid lithium which equals to 0.000503 Pa \( \cdot \) S. \( P \) is the pressure within the fluid. The lithium heat capacity \( C_p = 4349.2 J/kg \cdot K \). \( T \) is the temperature of the fluid. \( k \) is the heat conductivity of the liquid lithium which is 45 W/m \( \cdot \) K and it is assumed to be isotropic. \( S \) is the Seebeck coefficient of lithium with the unit V/K and this describes the voltage
that will generate from a temperature difference due to the Seebeck effect. Although the Seebeck coefficient is actually a function of the temperature it is assumed to be a constant value (25V/K [34]) here for simplicity since it does not change too much within the temperature range of the experiment. Π is the viscous heating. The electrical conductivity of liquid lithium $\sigma = 3.52 \times 10^6 Ohm^{-1} \cdot m^{-1}$. $\vec{j}$ is the current density and $\varphi$ is the electrical potential. $\vec{B}$ is the magnetic field and it is assumed to be constant in this problem.

The top surface is assumed to be insulated and have no shear force. The heat flux is described by the equation (2.3). The side wall is assumed to be insulated, adiabatic and has no-slip condition. No-slip condition is also used on the interface between the liquid lithium and the stainless steel tray. The bottom of the steel tray is cooled by a copper heat sink and is grounded.

This problem is hard to be solved analytically. Based on the Von Karman similarity, Jaworski developed a method to calculate the swirling velocity at the steady state from the measured temperature distribution on the interface between the liquid lithium and the stainless steel tray. The calculated velocity matches the velocity directly measured by particle imaging velocimetry (PIV) in the experiment [31].

The work presented in this thesis is the continuation of the above mentioned work. First the swirling velocity values are calculated under extended experimental conditions. Then the surface temperature of the swirling liquid lithium is directly measured by the IR camera. At last, the calculated velocity field is used to calculate the surface temperature and is compared to the IR camera data.

3.1 Velocity field

At steady state, the continuity equation and the Navier-Stokes equation can be solved in the cylindrical coordinate system for a Von Karman type similarity solution. Assuming a temperature profile $T(r) = A_1 - A_2 r^2$ and applying the angular momentum balance over the whole volume an equation about $\Omega$ can be derived as [30]
Here \( h \) is the height of the liquid and \( \Omega \) is the angular velocity. \( l \) is the scaling length which equals to \((v/\Omega)^{1/2}\).

\[
\hat{R} = \left[ \overline{\mathcal{U}} + \left( 1 + \overline{\mathcal{U}}^2 \right)^{1/2} \right]^{1/2}
\]

\[
\overline{\mathcal{U}} = \mathcal{U} - \frac{H_{\infty}}{8}
\]

\[
H_{\infty} = \frac{2R}{1+R^4}
\]

\[R = \left[ \overline{\mathcal{U}} + \left( 1 + \overline{\mathcal{U}}^2 \right)^{1/2} \right]^{1/2}\]

\( \overline{\mathcal{U}} \) is the Elsasser number which is defined as \( \sigma B^2 / 2\Omega \rho \). \( \delta_{\Omega} \) is defined as the boundary layer thickness which equals to \( l \). \( v \) is the kinematic viscosity which equals to viscosity \( \mu \) divided by density \( \rho \). \( C \) is the parameter related to the ratio of the current density in lithium and stainless steel which is defined as \( h\sigma/t\sigma_w \). The thickness of the stainless steel wall \( t \) is 6.5mm and the electrical conductivity of stainless steel \( \sigma_w = 1.35 \times 10^6 Ohm^{-1} \cdot m^{-1} \). All the related lithium properties can be found in Hanford report [28]. Through this equation the peak angular velocity \( \Omega \) can be determined numerically by balancing both sides of this equation.

Jaworski derives a form of the swirling velocity which is \( u_\theta = A\sqrt{r} \) [37]. The coefficient \( A = \Omega \sqrt{r_0} \) is determined by the peak angular velocity \( \Omega \) from equations 3.5-3.9. Here \( r_0 \) is the maximum experimental swirling radius which is 5cm. The angular velocity \( \Omega \) under different experiment conditions is summarized below. Based on above assumptions, the velocity field is calculated and a typical swirling velocity contour is plotted in figure 3.3 with the unit of m/s. Figure 3.4 is a plot of the rotation direction of the velocity. Both figure 3.3 and figure 3.4 are correspond to \( h=0.01m \), \( B=400G \) and power=300W.
In the experiment the temperature profile at the interface was reconstructed from the thermocouple array measurement based on equation (2.5) and table 2.2 which what have been discussed in section 2.4. Then the reconstructed interface temperature values are fit by the parabolic equation $T(r) = A_1 - A_2r^2$ to get $A_2$. After this, the angular velocity and the velocity
field can be calculated based on equations (3.5-3.9). The velocity values are gained when the height of the liquid lithium pool is 1cm and 1.5cm.

The reconstructed temperature profile of 1cm thick liquid lithium is summarized here while those results for 1.5cm thick lithium are from previous experiments [30].

Figure 3.5 Interface temperature reconstructions for 1cm liquid lithium when B is 33.2Guass
Figure 3.6 Interface temperature reconstruction for 1cm liquid lithium when B is 66.7 Gauss

Figure 3.7 Interface temperature reconstruction for 1cm liquid lithium when B is 134.6 Gauss
Figure 3.8 Interface temperature reconstruction for 1cm liquid lithium when B is 265Guass

Figure 3.9 Interface temperature reconstruction for 1cm liquid lithium when B is 399.2Guass
During these 1cm lithium tests the high voltage was 15kV and the beam current was 20mA. Different magnetic fields were used while the water cooling was always at 0.3GPM.

The interaction temperature distribution of 1.5cm lithium included in Jaworski’s thesis is summarized here [30].

Table 3.1 Summary of the reconstructed interface temperature profile for different magnetic fields

<table>
<thead>
<tr>
<th>Magnetic field [Gauss]</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>271</td>
<td>527.0</td>
<td>36342</td>
</tr>
<tr>
<td>406</td>
<td>599.7</td>
<td>57350</td>
</tr>
<tr>
<td>542</td>
<td>582.6</td>
<td>55612</td>
</tr>
<tr>
<td>677</td>
<td>538.6</td>
<td>38669</td>
</tr>
</tbody>
</table>

With the reconstructed interface temperature profile, the peak angular velocity of the swirling flow can be calculated.

Table 3.2 Summary of the peak angular velocities for different thicknesses of liquid lithium in different magnetic field

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>Ω [rad/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B=33.2Gauss, h=1cm</td>
<td>4.61</td>
</tr>
<tr>
<td>B=66.7Gauss, h=1cm</td>
<td>6.47</td>
</tr>
<tr>
<td>B=134.6Gauss, h=1cm</td>
<td>6.52</td>
</tr>
<tr>
<td>B=265Gauss, h=1cm</td>
<td>4.84</td>
</tr>
<tr>
<td>B=399.2Gauss, h=1cm</td>
<td>3.21</td>
</tr>
<tr>
<td>B=271Gauss, h=1.5cm</td>
<td>3.26</td>
</tr>
<tr>
<td>B=406Gauss, h=1.5cm</td>
<td>3.55</td>
</tr>
<tr>
<td>B=542Gauss, h=1.5cm</td>
<td>2.61</td>
</tr>
<tr>
<td>B=677Gauss, h=1.5cm</td>
<td>1.46</td>
</tr>
</tbody>
</table>
3.2 Surface temperature measurement

3.2.1 IR calibration

The emissivity of material usually is less than 1. In fact some theoretical calculation reveals that the emissivity of pure lithium is less than 0.1 [35].

Here we use the gray body assumption. Lithium was melted in the tray with a small heater attached to the back side of the tray. A thermocouple was immersed in the liquid lithium to record the temperature. The temperature was measured after lithium had been heated to a high temperature (~450C). Then the heater was turned off and the liquid lithium started to cool down by itself. During the cooling, the convective cooling system was off so the cooling only relied on the radiation and the contact between the stainless steel tray and its holding frame. Such a cooling process requires more than two hours to cool down to the room temperature. The thermal equilibrium time of the liquid lithium can be calculated by $\rho C_p / (k l^2)$ so it takes 22.6s for the temperature difference to drop below 1%. Here $l$ is the thickness of the pool of lithium. The thermal equilibrium within the liquid lithium is assumed after the liquid lithium started to cool.
down, which means the value that was measured by the immersed thermocouples is considered as the surface temperature.

Due to the infrared light emission from the background, the transmission of the ZnSe view port and the reflection of the polished aluminum mirror are hard to take all of these values into consideration and get an effective emissivity. Instead, an easier way is to measure the effective emissivity which compensates all the influence. In SandIR program an emissivity value can be assigned to the image so that the corrected temperature value can match the real temperature. In our experiment a series emissivity maps with different emissivity values assigned to the lithium area were prepared ahead of time. During experiment when the temperature started to drop, various emissivity maps were applied until the temperature readings on screen were closest to thermocouple readings. From this method we got an emissivity of 0.0468.

![Emissivity measurement graph](image)

Figure 3.11 In situ liquid lithium surface emissivity measurement on SLiDE. Based on the emissivity map adjustment in SandIR

In the same time the uncorrected temperature measurement from IR camera was also recorded. Emissivity can also be calculated with this equation:

$$\varepsilon (T^4 - T_0^4) = (T^*_c - T_0^4)$$  \hspace{1cm} (3.10)
Here $T$ is the real temperature from thermocouple. $T_\text{c}$ is the uncorrected temperature from IR camera and $T_0$ is the background temperature which was set to be 298K in experiment. The slope of the curve is the effective emissivity and it is 0.04673 and the error is 0.00542. So this method leads to a similar result as what we got above.

![Figure 3.12 Lithium temperature measured by IR camera vs. temperature measured by thermocouple](image)

After the emissivity is determined an emissivity map can be drawn and incorporated into SandIR program so that the surface temperature of liquid lithium can be directly read.

### 3.2.2 Surface temperature of swirling flow

The IR image of the swirling flow was taken when it was at steady state. Although the IR camera cannot measure the whole surface at the same time due to the e-beam blocking the light path, more than half of the surface area can be directly captured. In the SandIR software after the emissivity is adopted, the temperature can be read directly from the image at any position and when an IR image is taken the program will generate an array file to record the temperature at each pixel of this image.
Figure 3.13 A typical IR image of the liquid lithium surface directly taken from the IR camera control program (SandIR).

Figure 3.13 is a typical gray mode IR image of the swirling flow that is directly taken from the IR camera control program. The bright area represents the high infrared light emission region or generally speaking the high temperature region. Outside the blue line it is the stainless steel edge of the lithium tray. Inside is the lithium surface where we can see the dark region and the bright region. The impurity scale on the lithium surface, which is difficult to remove during the experiment, can increase the surface emissivity a lot so that it looks bright in the IR image although its real temperature should be similar to the nearby lithium surface. Fortunately most of the impurity scale concentrates close to the edge of the tray because of the centrifugal force and it will not disturb the measurement too much. Because of the swirling flow some part of the highly reflective liquid lithium surface may bend to the angle with which it can reflect the IR light from the e-beam filament into the IR camera and this reflection can be identified and labeled in the figure. Most of the dark region within the blue lines is the clean liquid lithium surface. Because of the low emissivity the lithium surface looks dark even though it is as hot as
the bright region. The swirling center is marked and some temperature values along a radial direction are labeled in SandIR and their units are Celsius.

In figure 3.13 the direct heating area by the electron beam is also marked on the image. However it is hardly to recognize this direct heating area since the temperature of the direction heating area seems not significantly higher than other part with the same radial position. It is also discovered that in one IR measurement the temperature distribution mostly relies on the radius position. The explanation will be discussed in the next chapter.

The radial temperature distributions of the IR measurements under different conditions are plotted. First the swirling center is labeled and the region that is disturbed by the reflection and the impurity layer is excluded. Then the temperature distribution along a radial direction where the lithium surface is clean will be measured.

The temperature measurements of 1cm and 1.5cm thick swirling flow are presented below. Temperature values are compared under different magnetic fields, different heating power, different thickness of lithium and different bottom plate material (Stainless steel and Molybdenum).

Figure 3.14, 3.15 and 3.16 compare the radial surface temperature profile under different heating power. In general higher heating power leads to a higher surface temperature while the temperature gradient along the radius direction does not change too much. In some figures such as figure 3.13, some part of the swirling flow may look much higher than the nearby area. This is caused by the reflection of the beam filament and the corresponding value should not be taken into consideration.
Figure 3.14 Radial surface temperature distribution of 1cm swirling lithium flow under different beam heating power in a magnetic field of about 400G

Figure 3.15 Radial surface temperature distribution of 1.5cm swirling lithium flow under different beam heating power in a magnetic field of about 400G
Figure 3.16 Radial surface temperature distribution of 1.5cm swirling lithium flow on Mo bottom plate under different beam heating power in a magnetic field of about 400G

Figure 3.17, 3.18 and 3.19 compare the radial surface temperature profile in different magnetic fields while the beam heating power is kept unchanged. The magnetic field can affect the heat transfer in two ways. Since the beam is focused by the magnetic field a higher field means a higher heat flux gradient on the lithium top surface. The center of the liquid lithium will suffer a higher heat flux when the magnetic field is higher. This was observed in experiments and also can be found from the IR results. In the experiments when the magnetic field is above a certain value the center heat flux leads to a significant evaporation at the swirling center and the lithium vapor is hit by the electron beam right above the lithium surface. The lithium vapor was excited and ionized so that it emits red glow. From the IR results we can also see this. Although most part of the lithium surface temperature does not change with magnetic field the center temperature increases with the magnetic field because of the increased center heat flux.

On the other hand the magnetic field can effectively change the swirling velocity but the surface temperature profile does not change a lot. As we know the azimuthal velocity does not change the temperature distribution on radial direction while the radial velocity is the secondary part of the velocity field, it is safe to conclude that the radial velocity change has little influence on the swirling flow heat transfer.
In the experiment, the swirling flow bends the free surface of liquid lithium and sometimes the center of the pool of lithium happens to bend to an angle that can reflect the light from the hot e-beam filament directly into the IR camera. In figure 3.18 the temperature measurements at the center meets with this problem.

Figure 3.17 Radial surface temperature distribution of 1cm swirling lithium flow in different magnetic fields with 300W beam heating

Figure 3.18 Radial surface temperature distribution of 1.5cm swirling lithium flow in different magnetic fields with 300W beam heating
Figure 3.19 Radial surface temperature distribution of 1.5cm swirling lithium flow on Mo bottom plate in different magnetic fields with 300W beam heating.

Figure 3.20 Radial surface temperature distributions of 1cm and 1.5cm swirling lithium flow on SS and Mo bottom plate in 400G magnetic fields with 300W beam heating.
The thickness of the swirling flow can affect the swirling velocity but as we discussed above, the change of the swirling velocity does not change the radial temperature distribution. Since \( T_{\text{surface}} = T_{\text{bottom}} + \frac{\partial T}{\partial z} \cdot h \) if the average temperature gradient along the z (height) direction is similar, the secondary flow along the height direction can be ignored. Then obviously 1.5cm Lithium flow should have a higher surface temperature.

When the bottom of the lithium tray is changed to Molybdenum the Seebeck coefficient between liquid lithium and bottom of the tray is changed. The thermoelectric power between Mo and Li is about half of the value of SS and Li. However since this value only affects the swirling flow velocity, the shape of the temperature profile does not change a lot when the bottom material is changed. However, the bottom material will affect the bottom temperature distribution. The heat conductivity of Mo is 140W/m*K [35] while that of SS is only 16 W/m*K. So the temperature gradient across the Mo bottom plate should be lower than the SS plate so that the bottom temperature profile of the swirling flow on Mo bottom plate should be lower than that on SS bottom plate. Even though we can assume that both cases have similar temperature difference between top surface and the bottom of the flow, the surface temperature of the swirling lithium flow on Mo plate should be lower than that on SS plate.
Chapter 4 Comparison between the IR results and the calculated results

4.1 Heat transfer analysis in the swirling flow

The heat transfer problem of the swirling flow can be described by

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \bar{u} \cdot \nabla T \right) = \nabla \cdot \left( k \nabla T - ST \bar{J} \right) + \Pi + \frac{j \cdot j}{\sigma} \]  \hspace{1cm} (4.1)

At steady state \( \frac{\partial T}{\partial t} \) equals to zero. Here \( \Pi \) is the viscous heating term which equals to \( \mu \Phi_v \cdot \frac{j \cdot j}{\sigma} \) describes the Ohmic heating with liquid lithium. The heat flux term is changed to \( k \nabla T - ST \bar{J} \) because the ordinary heat conduction heat can also be carried by the electric current due to Peltier effect.

To take the Seebeck effect into consideration the Ohm equation needs to be revised as

\[ \bar{J} = \sigma \left( -\nabla \varphi + \bar{u} \times \bar{B} - S \nabla T \right) \land \nabla \cdot \bar{J} = 0 \]  \hspace{1cm} (4.2)

Since the Seebeck current generates the only driven force in the Navier-Stokes equation, the induced current should always be smaller than the Seebeck current and the total current density should always be the same level as the Seebeck current density. As a result, it is convenient to assume that the total current density is \( \bar{J} = C \sigma \nabla T \). Here \( C \) is an arbitrary constant which is not far from one.

For the sake of simplicity, some dimensionless assumptions are postulated here. The velocity is taken to be \( \bar{u} = u_0 \bar{u}^* \) in which \( u_0 \) is a characteristic velocity. Similarly the temperature is assumed to be \( T^* = \frac{T - T_0}{T_{max} - T_0} \) in which \( T_0 \) is the melting temperature of lithium and \( T_{max} \) is the maximum temperature of liquid lithium during experiment. The operator \( \nabla \) becomes \( \nabla = \frac{1}{l} \nabla^* \) in which \( l \) is the characteristic length. The dissipation function \( \Phi_v \) is changed to \( \Phi_v = \frac{u_0^2}{l_0} \Phi_v^* \). With these dimensionless numbers, the heat transfer equation can be revised as
\[
\vec{u}^* \cdot \nabla^* T^* = \frac{k}{\rho C_p l u_0} \nabla^* T^* + \frac{\mu u_0}{\rho C_p l (T_{max} - T_0)} \Phi_{v}^* \\
+ C(C - 1) \frac{\sigma S^2 \left( \frac{(T_{max} - T_0)}{l} \right)^2}{\rho C_p l u_0 (T_{max} - T_0)} (\nabla^* T^*)^2
\] (4.3)

Or
\[
\vec{u}^* \cdot \nabla^* T^* = \frac{1}{Pe} \nabla^* T^* + \frac{Br}{Pe} \Phi_{v}^* \\
+ C(C - 1) \frac{\sigma S^2 \left( \frac{(T_{max} - T_0)}{l} \right)^2}{\rho C_p l u_0 (T_{max} - T_0)} (\nabla^* T^*)^2
\] (4.4)

Here the Peclet number Pe is the ratio of the heat transfer rate by the advection to the thermal diffusion rate and the Brinkman number Br represents the importance of the viscous dissipation term.

By examining the velocity field from the Von Karman similarity solution it is easy to find that a boundary layer exists between the bulk fluid and the surface of the bottom tray [30]. The boundary layer thickness is \( \delta = \sqrt{\frac{\mu}{\eta \rho}} \) and the radial and vertical velocities are comparable to the azimuthal velocity within 4\( \delta \) thickness. In our experiment the value of \( \delta \) falls to \( 4 \times 10^{-4} \sim 6 \times 10^{-4} \) m. For the bulk fluid the radial and vertical velocities are much smaller than the azimuthal velocity and can be ignored in the heat transfer equation.

To estimate the importance of each term in the heat transfer equation, values are assigned to the characteristic parameters. \( u_0 = 0.2 m/s, l = 0.05 m \) for azimuthal flow. \( (T_{max} - T_0) = 300 K \).

With these values, the Peclet number for the azimuthal flow is 492 which means in the azimuthal direction the convection is much more important than heat conduction. Although the beam heat flux is highly focused with a small area the swirling liquid lithium has a strong ability to transfer the heat along the azimuthal direction which may lead to a roughly axisymmetric temperature distribution. Here, although the shape of the tray is a square we assume circular shape for the above derivation. The above derivation also works for square shape. The coefficient in front of the dimensionless dissipation function \( \frac{Br}{Pe} \) equals to \( 3 \times 10^{-10} \) which means the viscous heating
is negligible. The coefficient of the Ohm heating \( \frac{\sigma s^2 ((T_{\text{max}} - T_0)/l)^2}{\rho C_p u_0 (T_{\text{max}} - T_0)/l} \) equals to \( 1.1 \times 10^{-4} \) so that the Ohm heating is also dropped in the calculation. However on the radius and vertical direction the characteristic velocity is almost zero which means the heat conduction is dominant on these two directions.

Based on these analyses the heat transfer equation is simplified to [36]

\[
\rho C_p u_\theta \cdot \nabla T = k \nabla^2 T \tag{4.5}
\]

In this equation only the azimuthal velocity is left in the convection term.

4.2 Calculation of the heat transfer equation

The calculation domain includes the liquid lithium region and the SS side wall. In figure 4.1 the pink lithium region is a 0.1m by 0.1 m square with a height of 0.01m or 0.015m. The lithium is surrounded by the 0.003m thick SS wall. The simplified heat transfer equation is solved in the lithium part while the SS part only has the heat conduction. In the lithium region only the swirling velocity is assigned to the heat transfer equation. Jaworski derives the form of the swirling velocity \( u_\theta = A \sqrt{r} \) [37]. The coefficient \( A = \Omega \sqrt{r_0} \) is determined by the peak angular velocity \( \Omega \) from equation 3.5~3.9 which is defined and calculated in section 3.1. Here \( r_0 \) is the maximum swirling radius in the experiment which is taken as 5cm.

Boundary conditions are necessary to solve this problem. The constant Gaussian shape heat flux is used on the top surface based on equation 2.4. The side wall of the tray is assumed to be thermally insulated since the thermal radiation can be neglected at the experimental temperature.

The whole domain is meshed and solved in the 3D finite element solver COMSOL.
Since the problem is solved in the Cartesian coordinates, the velocity field is approximated to be

$$u_x = \frac{-\Omega \sqrt{r_0 y}}{\sqrt{r}} \quad (4.6)$$

$$u_y = \frac{\Omega \sqrt{r_0 x}}{\sqrt{r}} \quad (4.7)$$
Here $r_0$ is the maximum experimental swirling radius which is taken to be 5cm. The peak angular velocity is given by table 3.2.

The boundary condition on the bottom surface is tentative. The temperature profile reconstruction process described in section 3.1 gives out the temperature distribution at the interface between the liquid lithium and the stainless steel. But this is actually the temperature of the SS part at the interface of SS and liquid lithium. Although the temperature must change continuously it is hard to say that the temperature change from the SS/Li interface to the bulk fluid can be described by the simplified heat transfer equation. Due to the existence of the Hartmann layer between SS bottom and bulk liquid lithium the real heat transfer within the Hartmann layer is unknown and can hardly be solved with this model when the velocity field of the Hartmann layer cannot be explicitly expressed. To compensate this problem a thermal resistance layer is built between the bottom temperature distribution boundary condition and the bulk fluid. In the thermal resistance layer, only the vertical heat conduction is solved and both the thickness and the heat conductivity of the thermal resistance layer are predefined in the calculation. To get a reasonable value of the thermal resistance layer, certain set of experimental conditions is used in the model and the thermal resistance layer is adjusted until the surface temperature with this particular group of experimental conditions can match the IR camera results. After that the thermal resistance layer property is fixed and used for all the other experimental conditions. The thickness of the resistance layer in this calculation is 150µm and its heat conductivity is 0.1 W/(m*K).

4.3 Comparison with experimental results

Through the calculation process defined in the last section the temperature distribution within the whole liquid lithium region can be calculated. Since the boundary condition on the top surface is only the inward heat flux profile the top surface temperature distribution will be plotted and compared to the IR measurements.
A typical surface temperature result is plotted here. In this situation the thickness of lithium is 1cm. The magnetic field is 400G and the e-beam power is 300W. The temperature distribution with zero swirling flow velocity is also plotted to reveal the step temperature gradient when only heat conduction exists. Clearly the dominant convection heat transfer redistributes the heat from the direct heating area to the other part with a similar radius. Instead of an elongated temperature profile in figure 4.4 the temperature contour in figure 4.3 looks axisymmetric. The color legends of both figures are set to be the same and the unit of temperature is K. The temperature values at the center of both figures are similar while the temperature gradient over the surface in figure 4.3 is much smaller.

Figure 4.3 Top surface temperature contour of liquid lithium.

\[ h=0.01 \text{m}, \quad B=400 \text{G} \quad \text{and} \quad P=300 \text{W}. \]
Figure 4.4 Top surface temperature contour of liquid lithium. h=0.01m, P=300W and the swirling velocity is set to be zero.

Under the same conditions as figure 4.3 the inner temperature distributions of the x-z plane when y=0 (perpendicular to the linear beam) and y-z plane when x=0 (parallel with the linear beam) are also plotted. Small difference between both pictures only exists at the center. The temperature of most part is almost the same due to the same k assumed in the vertical direction. The heat flux direction at the center is more likely downward while the direction of the flux with the radius larger than 0.02m is more outward. In general the temperature change along radial direction or vertical direction is smooth since it is assumed that there is no flow on these two directions.
To examine if the result from the calculation matches the real experiment the calculated surface temperature results (figure 4.6) are compared with those results directly measured with the IR camera (figure 4.7). The same experimental condition mentioned above is used here and figure 4.3 is modified to have the similar view direction as the IR image.

The IR measurement is plotted in color mode here to get a better discrepancy instead of the gray mode in figure 3.13. This is also clarified in section 3.2. The direct beam heating area is also marked in the IR image. In both temperature contour figures, the temperature is scaled to the same color legend. In both figure 4.6 and figure 4.7 we can see a hot swirling center within the direct heating area. Due to the fact that the view angle of the IR camera is not normal to the surface, only half of the lithium surface area can be seen in figure 4.7. However by comparing the area around the swirling center, we can find that the calculated result agrees with the IR camera measurement to some extent.
Figure 4.6 Top surface temperature contour of liquid lithium.

h=0.01m, B=400G and P=300W. Temperature along the dash line will be plotted and compared to experiment results.

Figure 4.7 Top surface temperature contour of liquid lithium measured by IR camera. h=0.01m, B=400G and P=300W.

The surface temperature profile along x direction when y=0 (along the black line in figure 4.6) is plotted and compared to the IR temperature measurements in section 3.2. In figure 4.8 the
surface temperature profiles are compared when the heating power is varied. The calculated value has a good agreement with the IR measurement. In figure 4.9 the surface temperature profiles are compared when the magnetic field is varied. The difference between the calculated value and the IR measurement is small for $B=134\,\text{G}$ and $B=400\,\text{G}$. However when $B=265\,\text{G}$, the agreement is not good. The calculated value seems higher than the IR camera result. This difference may come from the error of the bottom temperature profile reconstruction. This model relies on the accurate measurement of the SS-Li interface temperature profile as the bottom boundary condition.

Figure 4.8 Top surface temperature profiles comparison along $x$ direction (with $y=0$) between the calculated results and IR camera measurements. $h=0.01\,\text{m}$ and $B=400\,\text{G}$. 
Figure 4.9 Top surface temperature profiles comparison along x direction (with y=0) between the calculated results and IR camera measurements. \( h=0.01 \text{m} \) and \( P=300\text{W} \).

Figure 4.10 Top surface temperature profiles comparison along x direction (with y=0) between the calculated results and IR camera measurements. \( h=0.015\text{m} \) and \( B=400\text{G} \).

In figure 4.10 when the height of the lithium is changed to 1.5cm, the calculated temperature profiles are lower than the IR measurements but the difference is less than 50K. However, from
1cm lithium to 1.5cm lithium we actually dissembled the tray system, cleaned lithium and reloaded lithium. A few thin (0.001") copper shim stock layers are placed between the stainless steel tray and the thermocouple array and each time when we attach the stainless steel tray it is hard to say the thermal contact remains the same. The temperature reconstruction within the thermocouple array may change a lot due to this procedure and the reconstructed temperature profile at bottom may have offset problem from this error.

4.4 Discussion

Through a thorough dimensionless analysis, the heat transfer problem in the TEMHD swirling flow is well defined and simplified. The temperature distribution within the bulk liquid lithium is calculated and the resulting surface temperature of the fluid is compared to the surface temperature measured by IR camera. From the analysis in this chapter, it is concluded the TEMHD driven swirling flow with the dominant velocity in azimuthal direction [30] is the major direction of the convection heat transfer. On the other hand, the secondary velocity on the other directions is much smaller compared to the azimuthal one so that the convection in the other directions is less compared to the conduction, which means in other directions the liquid lithium can be treated as stationary liquid with pure heat conduction.

In figure 4.6 the hot swirling center looks like a yellow ellipse. Its major axis rotates about 11 degree compared to the direction of the beam (the direction of y axis). This is because the swirling flow tends to even out the temperature distribution to make the temperature contour look like a circle while the narrow heat flux tends to build a steep temperature gradient like figure 4.4. The total effect is the ellipse shape temperature distribution in figure 4.6.
Figure 4.11 Top surface temperature profiles comparison along x direction (with y=0) and along y direction (with x=0)

The temperature distribution on the top surface appears axisymmetric although a small difference still exists between the profile along the beam direction (y-axis) and across the beam direction (x-axis). This can also be seen from figure 4.6. This difference depends on the heat flux gradient of the beam and the rotational speed. When the Peclet number is large enough, the difference will disappear.

This brings up a question. What is the minimum velocity of the liquid lithium flow to be convection dominated? If the Peclet number is set to be one the velocity needs to be about $4 \times 10^{-4} \text{m/s}$ so that the convection is comparable to the conduction. This truth reveals that liquid lithium can be convection dominated with a small velocity and within the boundary layer the Peclet number may be larger than one since the velocity within the boundary layer may be higher than $10^{-3} \text{m/s}$ according to the velocity field calculation from Von Karman similarity [30].

Based on the above analysis, the assumptions that the heat transfer across the boundary layer can be compensated by a thin thermal resistance layer for different magnetic fields, top heat fluxes or height of the flow is actually valid. However since the boundary layer may be convection dominated and the velocity field within the boundary layer is affected by the experimental conditions the overall thermal resistance across the thermal barrier layer needs to be calibrated.
for different Hartmann number with the method from section 4.2 in order to get a better agreement with the IR measurements.

The melting lithium experiment in CDX-U can be reconsidered now. During that experiment the magnetic field is about 200~400G. The electron beam is 1.5kW and the beam spot is a 6mm diameter circle, which results in about 60MW/m² heat flux on the lithium surface. All these conditions are similar to SLiDE except that the heat flux is much higher. The surface was monitored by an IR camera and no significant evaporation was discovered. The liquid lithium swirled as SLiDE experiment and no apparent radial flow was seen. Comparing figure 4.3 and figure 4.4 we can see that the swirling flow strongly affects the radial temperature distribution. But since the flow has a small vertical component it cannot accelerate the vertical heat transfer. When the heating area is a circle the conduction cannot lower the temperature at the direct heating area if the velocity is mainly swirling as what was observed in experiment.

During the experiment on CDX-U, the center temperature of the swirling lithium is not much hotter than the nearby region. In that experiment the thickness of the liquid lithium is only 5mm and the Hartmann number is less than 17. The Hartmann layer thickness is about 0.3~0.6mm which can be considered as a characteristic length δ of the boundary layer. Through the bulk lithium the TEMHD provides an azimuthal driven force to force the lithium to swirl. At each point the centrifugal force also generates the secondary radial flow. But in the TEMHD driven swirling flow, the radial flow only exists within 5δ thickness [30] which means during the CDX-U experiment almost one third to half of the lithium has such radial flow under the surface, which may effectively bring the cooler liquid lithium inward and cool down the center area. Also because the thickness is smaller than our experiment the vertical heat conduction is more efficient.
Chapter 5 Conclusions and future work

The concept of using flowing liquid lithium as the PFC material especially the divertor has drawn a lot of interests these days. The experiment on CDX-U found that the free surface liquid lithium can swirl by itself under the uneven heating and the magnetic field. Such flow has a great potential to mitigate the peak heat flux from the plasma. The mystery of the CDX-U experiment was uncovered by a series of experiments designed and performed in University of Illinois which proved the TEMHD driven force to be the key phenomenon for the swirling flow. The velocity field of this type of flow was calculated and also measured directly.

Based on the determined velocity field of the TEMHD driven swirling flow, this thesis has analyzed its heat transfer. An IR camera system has been built and calibrated to measure the surface temperature distribution of the lithium with 14 embedded thermocouples as a supplement. Although the heat transfer equation is fully coupled with the Navier-Stokes equation, a simplification is developed to calculate the temperature distribution of the bulk fluid based on the measured velocity field and thermal boundary conditions. The heat transfer equation is simplified by assuming the axisymmetric temperature distribution on the boundary and neglecting the unimportant convection terms on radial and vertical directions. A 150µm thermal resistance layer is postulated between the bottom tray surface and the bottom of the fluid to compensate the error from the thermocouple measurements and heat transfer in boundary layer for all cases.

With these assumptions, the calculated surface temperature distributions agree with the results measured by IR camera system to some extent. The heat transfer inside liquid lithium is found to be highly convective. The convection is strong along the azimuthal direction while the heat conduction is more important on the perpendicular directions to the dominant velocity direction. The boundary layer is important to the temperature distribution and especially the heat interaction at the interface. The boundary layer between the liquid lithium and the stainless steel wall can affect the flow and heat transfer of the whole liquid lithium flow.

The next step of this work is to find out how the heat and momentum exchanges between the boundary layer and the bulk fluid. It seems that the flow within the boundary layer is subjected to the magnetic field, the fluid thickness and the flow velocity of the bulk fluid. To build a feasible
model may end up solving the coupled Navier-Stokes equation and heat transfer equation simultaneously. Instead, computationally solving full set of Navier-Stokes equations, heat transfer equation and Ampere equation within the bulk fluid and the boundary layer may be another choice.

In experiments, the thickness of the liquid lithium can be lowered to investigate the effect of the thickness on the flow and heat transfer. The heat flux from the beam needs to be increased while the power of the beam should not increase beyond the cooling capability of the heat sink. It is believed that at the same magnetic field if the thickness of the liquid lithium is lowered from 2cm to 0.2cm the maximum heat flux that the surface can handle may first increase linearly with the thickness and after a certain point starts to be more efficient than linear because the boundary layer thickness becomes comparable to the thickness of the lithium.

Another interesting topic is how the heat transfer acts under the high magnetic field. When the Hartmann number is more than a few hundred, the boundary layer thickness will be less than 1% of the total thickness. So the temperature at the direct heating area will increase although the heat flux and total thickness are kept unchanged.

More work can be done to find out the reason for the dry-out effect of the lithium flow. It is found that after the beam power exceeds a certain point or the magnetic field is stronger than a certain value the center of the swirling flow will become empty and the center SS tray will be directly exposed to the electron beam. This phenomenon is believed to be related with the Marangoni effect. The surface temperature distribution reveals a high temperature gradient along the radial direction and cannot be removed by the swirling flow. Such a temperature gradient may generate a capillary force along the radial direction and drag the liquid out of the center of the swirl. Because of this radial force, the center of the pool becomes dry.

Some initial work of using TEMHD driven liquid lithium as a self-cooling PFC has been done. Our experiments proved that TEMHD driven open duct flow can effectively transfers the heat away from direct heating area. [32]
References


[33] Inframetrics 760 manual

