TRANSIENT EVAPORATION INDUCED BY HIGH ENERGY LASER-MATTER INTERACTION

A Thesis in
Aerospace Engineering

by

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ABSTRACT

Surface evaporation of material induced by a high power laser is an important physical process that plays a significant effect in heat transfer and material removal. Currently, a detailed model that allows accurate prediction of evaporation rate and recoil pressure is under development at Applied Research Laboratory of the Penn State University. Such a model will be a crucial component for science of directed energy weapons lethality, as well as combustion, environmental and material sciences of which all will benefit from improving understanding of the physics of this process. Through a series of experiments material including iron, aluminum, nickel, Inconel, and zinc are examined in atmosphere and vacuum. The experimental data are collected at the laser effects experimental facility of the Penn State Electro-Optics Center using an IPG 10 kW fiber laser. The results of experimental measurements of evaporation rate as functions of surface temperature and laser intensity are reported. Observations and measurements taken of the interaction of the IPG 10 kW fiber laser are discussed and analyzed in order to describe the physical processes taking place. The data are compared with the predictions of the new theoretical model that is currently under development with funding support from JTO/AFOSR as part of MRI.
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NOMENCLATURE

\( f \) = distribution function
\( n \) = number density
\( m \) = molecular weight
\( k \) = Boltzmann constant
\( T \) = temperature
\( v \) = velocity of a particle
\( J \) = evaporation rate [mass/time-area]
\( \sigma \) = coefficient of evaporation or condensation
\( s \) = subscript indicating surface conditions
\( \infty \) = subscript indicating conditions far from the surface
\( u \) = steady velocity
\( P \) = pressure
\( R \) = specific gas constant
\( L_v \) = heat of vaporization
\( H \) = enthalpy evaporation
\( C_p \) = specific heat at constant pressure
\( \varepsilon \) = cohesive energy of a single atom
\( \kappa \) = thermal conductivity
\( \alpha \) = thermal diffusivity
\( r \) = surface reflectivity
\( I \) = laser intensity
ACKNOWLEDGEMENTS

I’d like to thank JTO for providing the funds necessary to conduct this research as well as AFOSR, Program Manager Dr. John Luginsland for managing the project. I would also like to thank the personnel of the Applied Research Lab, Jeff Thomas and the staff of the Electro Optics Center, Jay Tressler at ARL Research West, and Josh Stapleton of the Materials Characterization Lab at Penn State for all their support and assistance. Thank you also to Dr. Micci for all the guidance and advice he provided. I would like to thank Dr. Semak and Dr. Miller of the Applied Research Lab as well. Their guidance on this project was extremely valuable. Finally, thank you to all my family and friends for all their encouragement and support.
Chapter 1
Mass Transfer Theory during High Power Laser - Matter Interaction

The interaction of a high power laser with matter is an important subject that has wide ranging applications. The processes involved have been under investigation by numerous individuals since the development of the laser itself. The subject of high power laser – matter interaction has applications such as laser welding and directed energy weapons. It is important to advance our understanding of the processes involved in order to improve performance in applications of high power lasers and be able to understand and predict their effects.

One of the critical effects induced by a high power laser acting upon a condensed material is that of evaporation. The theory of evaporation dates back to publications by Hertz in 1882. Many have studied the theory in years following his publications. Currently the theory relies upon experimentally determined coefficients that correspond to specific materials to predict the mass transfer resulting from the evaporation/condensation process. This theoretical approach is not particularly accurate in predicting the mass transfer. This is largely affected by a wide range of disagreement on the coefficients. This thesis examines this theory, applies it to laser-matter interactions, and reports experimentally measured evaporation rates and how they compare to improved theoretical equations under development.

Current Theory of Evaporation

Current theory of evaporation is based on what was originally published by Hertz in 1882 (1). It has since been expanded upon by individuals such as Schrage and others (2). Many of the past studies of evaporation have focused on water. This is because it is common, affects many
different subject areas, and is easy to obtain and work with in experiments. The theory of
evaporation can; however, be applied to any material. The different characteristics, for example
atomic mass, must simply be taken into account. This theory is important to understanding what
occurs during the interaction of a high power laser with some material.

**Hertz’s Fundamental Theory**

Assume a pure substance is experiencing evaporation and condensation on a flat surface.
Particles can be assumed to be moving along a single axis out of the surface. At the interface
between the gas and the condensed phase there is assumed to be a saturated vapor region. The
particles in this region are assumed to be in a Maxwellian distribution with the particles having
properties of surface temperature and saturated vapor pressure. The gas particles above the
surface that could potentially condense are also assumed to be in a Maxwellian distribution at
conditions that are far from the surface. According to Hertz, the maximum theoretical mass flux
due to evaporation is the integral from zero to infinity (negative infinity to zero for condensation)
of the distribution function multiplied by the particle mass and velocity. A Maxwellian
distribution function is represented by the Eq. 1 below (1).

\[
f = n \frac{m}{\sqrt{2\pi kT}} \int e^{-\frac{mv^2}{2kT}} dv_x
\]

(1)

The concept of the evaporation and condensation coefficient is then applied. The
evaporation coefficient is defined as the ratio of the experimental number of particles escaping
the condensed phase to the theoretical maximum number of particles escaping the condensed
phase. The theoretical number being the distribution function integrated from zero to infinity.
The condensation coefficient has a similar definition, only opposite such that condensing particles have a velocity from 0 to negative infinity. These coefficients are represented by the Greek letter sigma, “σ”.

The distribution function integrated from 0 to infinity for the saturated vapor region is multiplied by the evaporation coefficient, the velocity term, and the atomic mass of a particle to yield the flow rate per unit area of evaporation. Similarly the distribution function integrated from negative infinity to zero is multiplied by the condensation coefficient, the velocity term, and the mass of a particle to yield the flow rate per unit area of condensation. The flow of condensing particles is subtracted from the flow of evaporating particles to give the total mass flux. This is seen in Eq. 2 (2).

\[
J = \sigma_e m s \sqrt{\frac{m}{2\pi k T_s}} \int_0^\infty v_x e^{-\frac{mv_x^2}{2kT_s}} dv_x - \sigma_e m n_{\infty} \sqrt{\frac{m}{2\pi k T_{\infty}}} \int_{-\infty}^0 v_x e^{-\frac{mv_x^2}{2kT_{\infty}}} dv_x
\]

The assumptions of Maxwellian distributions can be combined with an assumption that the condensing particles are at a temperature and pressure equal to that far from the wall. This is indicated by a subscript of infinity. The ideal gas equation is also used to substitute in for, “n”, the number density. This allows the equation to be simplified down to the Hertz-Knudsen equation shown below as Eq. 3 (2).

\[
J = \sqrt{\frac{m}{2\pi k}} \left( \frac{\sigma_e P_w}{T_w} - \frac{\sigma_e P_{\infty}}{T_{\infty}} \right)
\]
**Coefficients of Evaporation and Condensation**

The coefficients of evaporation and condensation are used to adjust the theoretical equations to match what is seen experimentally. The coefficients are used to account for why experimental data does not match the theoretical maximum. This fraction is stated to be a result of the reflection of some of the particles that attempt to cross the interface. It is unclear what all the processes the coefficient will be accounting for and not all the contributing factors to the coefficients are well understood. In various studies performed by a number of individuals, a wide range of values have been obtained for the coefficients for water. This is thought to be the result of inaccurate temperature and pressure measurements, chemical impurities, differing experimental techniques, as well as other factors. It has been theorized that if all unknowns were eliminated the coefficients would be unity (3) (4). The exact nature and controlling factors of the evaporation and condensation coefficients have not yet been well understood.

In order to determine the coefficients, assumptions are made concerning equilibrium and non-equilibrium conditions. Under the equilibrium assumption the evaporation coefficient must be equal to the condensation coefficient. Under non-equilibrium conditions it is assumed that the evaporation rate is unaffected by the vapor phase (it remains constant) and will be equal to the number of vapor molecules striking the surface under equilibrium conditions; only the condensation coefficient is affected by non-equilibrium (5). Through a variety of experimental techniques, the evaporation rate has been measured under conditions in which there will be nearly zero condensation. This is thought to be the value that the condensation coefficient approaches as the system approaches equilibrium.
Schrage’s Correction

The Hertz-Knudsen equation is a simplified version that results from the assumptions. This form is inaccurate when the condensed material causes a negligible disturbance to the equilibrium established by vapor-vapor collisions. In the case of a flat surface, there is a net flow of vapor along the axis out of the surface. A stationary Maxwellian distribution function does not describe this well. If we designate the velocity of the vapor flow as “u”, then we can correct the Maxwellian distribution function as seen in Eq. 4 below (5).

\[
f = n \frac{m}{\sqrt{2\pi kT}} \int e^{-\frac{m(v_x-u)^2}{2kT}} dv_x
\]

(4)

This adjusted distribution function is used to describe the vapor molecules far from the surface. This does not apply to the distribution function describing the saturated vapor region at the wall because of the molecular collisions.

When this adjusted distribution function is used in the equation for mass flux and then integrated and simplified it results in a more accurate yet more complex equation. This can be seen as Eq. 5 (5).

\[
J = \frac{m}{\sqrt{2\pi k}} \left[ \frac{\sigma_e}{\sqrt{T_w}} \frac{P_w}{1 - \frac{1}{2} \sigma_c} - \frac{\sigma_c}{\sqrt{T_\infty}} \frac{P_\infty}{1 - \frac{1}{2} \sigma_c} \right]
\]

(5)
Equilibrium and Non-equilibrium

When in equilibrium the flux due to evaporation equals that due to condensation. The coefficients are also equal (6). Because the coefficients are equal, this ideal case is used to find the coefficients. The condensation coefficient is measured and then according to theory the evaporation coefficient is known. In this state the evaporating particles have a temperature equal to that of the surface of the condensed phase and the pressure is the saturated vapor pressure. The vapor particles attempting to condense are assumed to be at the conditions far from the wall. Referring to the mass flux equation the densities are usually defined by the ideal gas law. For evaporation the pressure in the ideal gas law is the saturated vapor pressure found with the Clausius-Clapeyron equation. The integrals for both the evaporation and condensation terms are similar but will be slightly different due to different temperatures as will the values of density. Equilibrium is an ideal case and will not be true of most practical situations. The assumption of an ideal gas also may not be appropriate in all situations.

Non-Equilibrium is the state in which there is a net mass flux; therefore, the evaporation and condensation fluxes are not equal. This is the situation in most practical applications. The absolute rate of vaporization is considered to be a function of the thermodynamic properties of the surface of the condensed phase (temperature and saturated vapor pressure). The absolute rate of vaporization is assumed to not be influenced by the state of the gas. The rate of condensation will be dependent upon the state of the gas and the surface. The coefficient of condensation is found through experimental measurements and used to compute the rate of condensation at the measured state of the gas (5).
Clausius-Clapeyron Equation

The Clausius-Clapeyron Equation is the equation describing the pressure corresponding to a particular temperature at which two phases are in equilibrium with each other. It defines the line on a pressure-temperature plot that separates the two phases.

The Clausius-Clapeyron equation is derived from some fundamental thermodynamic principles such as the state postulate, first law, and others. The common form of the equation is an approximation. For a liquid-gas phase change the specific volume of the gas is far greater than that of the liquid. The change in volume is changed to the volume of the gas phase in the equation. Then for lower pressures the gas can be treated as ideal and the ideal gas equation can be substituted in for the volume. These assumptions lead to the common form of the Clausius-Clapeyron given as Eq. 6 (7). Note also that the heat of vaporization is kept constant in this equation. In reality it will be a function of temperature.

\[ P_{\text{sat}} = P_0 e^{-\frac{L_v}{kT}} = P_0 e^{-\frac{L_v}{kT}} \]  

(6)

The heat of vaporization changes with temperature. In order for the Clausius-Clapeyron relation to be more accurate it should take this into account. We can make use of Kirchhoff’s law shown in Eq. 7 (7).

\[ \Delta H = H_0 + \int_0^T \Delta C_p dT \]  

(7)

The \( H_0 \) term is the enthalpy of evaporation at 0K and the integral represents the added enthalpy of evaporation for temperatures above 0K. Once more we can assume that the gas is
ideal such that \( C_p = C_v + R \) and Kirchhoff’s Law can be substituted into the Clausius-Clapeyron equation to yield Eq. 8 (7).

\[
\ln P = -\frac{H_0}{RT} + \frac{5}{2}\ln T - \frac{1}{R} \int_0^T C_p d(\ln T) + \frac{1}{RT} \int_0^T C_p dT + C
\]

(8)

The “C” term is the constant of integration. In order to evaluate this one needs to know the constant of integration and the temperature dependence of the \( \Delta C_p \). Because \( \Delta H \) and \( \Delta C_p \) vary slowly with temperature, the change in \( \Delta H \) can be approximated with the following simple expression in Eq. 9 (7).

\[
\Delta H = A + BT + CT^2
\]

(9)

This substituted into the Clausius-Clapeyron equation gives us Eq. 10 (7) shown below.

\[
\ln P = -\frac{A}{RT} + \frac{B}{R}\ln T + \frac{C}{R}T + D
\]

(10)

In this form D is the constant of integration. The above equation makes the heat of vaporization a function of temperature (7). This will lead to more accurate results. The empirical equations plotted later in this report are of this form.

In the referenced book, The Physical Properties of Liquid Metals (7), the Clausius-Clapeyron equation is derived and empirical data presented. They have developed empirical equations to represent measurements of saturated vapor pressure. The empirical equations make the heat of vaporization a function of temperature as was shown above. The theoretical and
empirical equations have been plotted for three elements between their melting points and their boiling points in order to evaluate the accuracy of the theoretical equation in Figures 1-3 (7).

**Aluminum**

![Graph for Aluminum](image)

**Titanium**

![Graph for Titanium](image)

---

**Figure 1-1** Saturated Vapor Pressure vs. Temperature for Aluminum

**Figure 1-2** Saturated Vapor Pressure vs. Temperature for Titanium
One can see from the plots shown that the Clausius-Clapeyron equation varies from the empirical data. It is not completely accurate and therefore will introduce a source of error into the evaporation mass flux predictions. This discrepancy is because the heat of vaporization is kept constant in this simplified form of the theoretical equation while it varies with temperature in the empirical equations. The error in the equation for the saturated vapor pressure contributes to the error resulting from the use of the Hertz-Knudsen equation to calculate the evaporation flux. In chapter 3, the results of the Hertz-Knudsen equation are plotted alongside experimental results to illustrate the inaccuracy of this theory.

**Discussion of Existing Theory**

The theory for evaporation and condensation reviewed in the previous part of this document is flawed. There are also wide ranges in disagreement on the evaporation coefficient
for materials such as water which is the result of inaccuracies, unknowns, and varying experimental setups. This is not a good approach to predicting mass flow rate per area due to evaporation or to understanding the process. One ought to be able to better understand the molecular behavior of the condensed and vapor phases and apply it to predicting the mass flux.

Our understanding of molecular dynamics and intermolecular forces has improved greatly since this approach to finding the theoretical evaporation rate was first developed. Our understanding of intermolecular forces should be applied to evaporation theory in order to better understand what is happening. In a condensed phase there are molecules bouncing around due to random thermal motion corresponding to a particular temperature. The condensed molecules can be assumed to be in a Maxwell distribution at some surface temperature with a density similar to the density at the melting point of the material. Now consider why these molecules stick together in the first place. Why don’t the molecules separate and disperse as they collide with each other and bounce around? It is because of the attractive forces between molecules, i.e. intermolecular forces. These molecules are held together by the potential energy between molecules. These intermolecular forces are a result of many contributing factors such as Lennard-Jones Potential, Covalent Bonding, Ionic Bonding, Hydrogen Bonding, and others. So each molecule has a certain amount of potential energy holding it to its neighbors. This energy is called cohesive energy. This relates to the latent heat of vaporization or heat of evaporation which is the energy required to vaporize a mole of the substance. The cohesive energy experienced by an individual molecule is the energy it must obtain in order to escape the potential well of its neighbors and become a vapor molecule (8).

So with this knowledge one knows the energy requirement for a molecule to evaporate. This means we know which molecules in the Maxwellian distribution of the condensed phase will evaporate. Any molecule that has energy greater than the cohesive energy will escape to become vapor. Integrating the Maxwell distribution function from the value of cohesive energy, $\varepsilon$, to
infinity will yield the number of particles evaporating. This is applied to the mass flux equation and shown as Eq. 11. Note that the density is now that of the condensed material and not of the saturated vapor. This could perhaps be approximated as the density of the material at its melting point. The mass flux has units of mass per unit time per unit area. This theory is already used in the evaporative cooling of a trapped gas in which gas molecules are in a magnetic trap and only those with enough energy can escape. Once they escape the molecules rethermalize to a lower temperature at a Maxwellian distribution (9).

\[ J_{\text{evaporation}} = mn_s \sqrt{\frac{m}{2\pi kT_s}} \int_0^\infty \frac{m v_x^2}{2\pi} e^{-\frac{m v_x^2}{2kT_s}} \, dv_x \]

(11)

The flux due to condensation should be improved upon as well. Condensation will be dependent upon many factors such as temperature and pressure of the free stream, the properties of the evaporating particles and their effect on the distribution, the net flow rate of the gas, the interaction of the vapor molecules with the condensed molecules, as well as other factors. The distribution function may not be Maxwellian. The ideal gas law may not apply. The presence of species other than the evaporating element should be considered. This could lead to changes in flux as well as oxidation and other effects. The reflection of molecules that are trying to condense should be considered as well. This will impact the magnitude of the flux as well as the transfer of momentum and energy to the surface. The fraction of condensing molecules that are reflected will be related to the temperature, collision cross section of the molecule, as well as other factors.

These concerns and others are being addressed in new theoretical equations under development at the Applied Research Laboratory at Penn State by Dr. Vladimir Semak. This new
system of equations, once numerically solved, will provide a far more accurate prediction of the transient mass transfer process that occurs during laser-matter interaction.

**Development of New Theory**

A new theory is under development at ARL to improve upon existing theory. A system of equations of mass, momentum, and energy transfer are being worked on as a part of this theory. These equations, once completed, will provide a means of making more accurate predictions than is currently possible.

A preliminary plot of predictions made by the theory still under development has been included in Figure 1-4 and is plotted with the prediction made by Hertz-Knudsen equation (2). One can see that the new theoretical predictions made by the equations being developed by Dr. Semak of the Applied Research Lab at Penn State are higher than that of Hertz-Knudsen. These predictions are closer to the evaporation rates seen in experiments.

![Figure 1-4 Preliminary Predictions of New Theory Compared with Hertz-Knudsen](image-url)
Upon completion of the new theoretical equations, the solution will be found numerically and compared with experimental measurements and old theoretical predictions. The new theory will be evaluated and presented in future publications.
Chapter 2

Setup and Operation of Laser-Matter Interaction Experiments

In order to examine the results of laser-matter interaction and test theoretical predictions, a series of tests were conducted. These tests experiments were run at the Electro-Optics Center of the Pennsylvania State University. Technicians at the Electro-Optics Center ran tests in which a high power laser interacted with several different materials at various spot sizes and power levels. Thermal data was taken and the samples were examined using an optical profilometer. This series of experiments was divided into two rounds of testing. In the first round of testing samples of aluminum, iron, and titanium were exposed to a laser. Upon examination of the laser-matter interaction effects it was determined a second round of testing was needed. The second round of testing examined some of the same materials but included new ones as well. Aluminum, iron, nickel, Inconel, and zinc were tested. In the second set of tests, the exposure time was decreased along with the laser intensity in order to decrease the effects of melt flow and ejection. The new material was added to the tests to investigate the transient evaporation, induced from laser-matter interaction, of corrosion resistant materials. The data from these experiments is analyzed in Chapter 3.

The Electro-Optics Center

The Electro-Optics Center is run by the Pennsylvania State University. It is located in Freeport, Pennsylvania. Its goal is to nurture the development of electro-optic materials, components, and transition successful technologies needed for the advancement of the nation's defense capabilities. The equipment provided by the Electro-Optics Center that was used in the
The first experiment was prepared in advance in the laboratory. During testing, the laser and data collection equipment were operated by trained technicians. One by one the samples were exposed to the test conditions. The data collected was compiled and submitted to Brian Taylor at the Applied Research Laboratory for analysis.

**First Set of Experiments**

The first group of experiments exposed aluminum, iron, and titanium to a high power laser. The samples were in regular atmospheric conditions. A low velocity horizontal flow of air was present due to an exhaust system that was put in place to remove metallic vapors resulting from the tests. The laser, focused and reflected through lens and mirrors, was directed onto the top surface of the square samples that lay supported on either side over a gap in the table. A graphite block was placed below the sample to absorb laser light that did not hit the sample. One thermal couple was placed below the sample in contact with the bottom surface, opposite the side interacting with the laser, to measure temperature. An infrared camera was used to measure the temperature at the top surface of the sample. It recorded the temperature of the surface in real-time. The equipment was run from a control room separated by glass designed to protect personal from stray laser light. Due to safety, the room was evacuated prior to each test. A diagram of the test set up is provided in Figure 2-1 below.
The samples themselves were cut into approximately 1.5 inch by 1.5 inch blocks. This size was chosen to be convenient as well as to allow ample surface area for laser-matter interaction. The samples were of varying thicknesses to account for the different heat transfer rates for the different materials. In Figure 2-2, one can see some of the samples displayed on a work bench.
Test Conditions and Data Collected

The conditions of the test were chosen such that the transient evaporation taking place could be measured over a range of power intensities and surface temperatures. The intensity of the laser acting upon the surface of the material was changed in two ways. The overall power level of the laser was changed and the spot size was changed. This allowed for a range of intensities to be tested for each material. The power was varied between 4 and 10 kW and the spot size was changed between 15 and 5 millimeters in diameter. For different intensities the samples were exposed for different lengths of time to examine different levels of evaporation rate. Tables 1 and 2 below show the power levels and spot sizes tested for Aluminum and Iron.

<table>
<thead>
<tr>
<th>Table 1  Test 1 Conditions for Aluminum.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Test Conditions</td>
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<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Power Levels (kW)</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Spot Diameter (mm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2  Test 1 Conditions for Iron.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Test Conditions</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Power Levels (kW)</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Spot Diameter (mm)</td>
</tr>
</tbody>
</table>

In addition to the test conditions, temperature measurements were recorded for the top surface (the surface upon which the laser was acting) by using an infrared camera. Temperature was also measured on the opposite side with a thermocouple. The temperature measurements were taken so that the evaporation rates could be compared to the surface temperature. This corresponds to the theoretical equations in which the evaporation rate is a function of surface
temperature. Optical Profilometry was used to measure the maximum depth and surface features of the evaporated zones of the material. Figure 2-3 below show an example of a 3-D plot of the intensity of one of the laser configurations. The form of the laser can be examined and used to better understand the interaction process. The laser is not perfectly symmetric and has multiple peak intensities near the center of the beam. The result of this can be seen in infrared videos and explains why in some instances individual hot spots can be seen. This may also explain some of the movement of molten material observed on the infrared videos and the shape of the surface features. See Figure 2-3 below to see a 3-D plot of the laser intensity for a 1 cm beam at 10 kW in which the vertical axis is intensity and the other two axis are number of pixels.

Figure 2-3 Intensity Profile of a 1 cm Diameter Beam in W/cm²
Analysis Using Optical Profilometry

Equipment Description

Upon completion of the experiments at the Electro-Optics Center the samples and data were sent to Brian Taylor at the Applied Research Laboratory for analysis. The samples were examined with an optical profilometer, the NewView 7300 model, manufactured by the Zygo Corporation. The corresponding software used in the operation of the profilometer and the analysis of the data was MetroPro, which was produced by the same company. This equipment and software was provided by the Materials Characterization Laboratory at Penn State University located in the Millennium Sciences Building on the University Park campus.

The optical profilometer is capable of imaging the surface of materials with resolution on the scale of nanometers. The software can create two and three dimensional images. It can also create profile plots of surface depth, calculate the changes in volume difference with respect to a plane, and perform many other analyses of the surface. It has a wide range of applications and is a valuable tool.

The profilometer is a white light interferometer system. Optical interferometry combines multiple light waves such that interference occurs between waves. This is done through optics equipment. This technique can be used to provide detailed imaging of surfaces on very small scales.

Operation of Equipment

When using the profilometer to analyze a sample the z-stop must be set to protect the aperture from striking the sample. One of the key features to select from is the aperture size. The 2.5x aperture was used to provide the largest field of view to image the large (in comparison to
features it is usually used to image) features resulting from the laser-matter interaction. An extended scan is used to scan from the deepest surface feature to the highest. The extended scan allows the profilometer to scan over its maximum range, which is 2mm vertical distance. The software has the ability to take multiple images and stitch them together to image large surface features as is the case with these samples. The data from the image, once stitched together, is displayed in the software. This software, while being the means by which the profilometer is controlled, is also used for data analysis. Two and three dimensional images are created. Depth profiles and volume above and below a reference plane can be found. This software has many functions and is a versatile tool.

**Second Set of Experiments**

It was determined that a second set of tests was necessary in order to obtain more accurate measurements of the rate of evaporation. Specifically the influence of melt flow and ejection needed to be decreased. The flow and ejection of molten material during the high energy laser interaction affects the depth of the resulting surface feature; therefore, contributing to the measurement of the removal rate of material. The goal of the second set of experiments was to decrease this effect as well as test and measure additional materials.

The second set of experiments was conducted similarly to the first with some key changes. These tests were conducted at the Applied Research Laboratory facility located in the research west building located on the Penn State campus. Although aluminum and iron were tested again, titanium was not. It was observed that under the heat of the laser the titanium expanded in volume, due to corrosion and possibly a change in the atomic structure of the metal. It was determined that this made it unsuitable for further testing due to the fact that this prevented
the measurement of mass removal from the surface with the current available method. New materials were included in the test to expand the investigation into how the rate of evaporation changes with surface temperature and laser intensity. The new materials added to the experiment include nickel, Inconel 625 (which is an alloy of nickel commonly used in aerospace applications), and zinc. There was interest in examining the laser-matter interactions with zinc and nickel due to their low corrosion rates. Inconel is commonly used in the aerospace industry and was also of interest due to potential applications of high power lasers in this field. The second group of samples was exposed to lower intensities over shorter exposure times to minimize the effect of melt flow and ejection. There was consideration of using a vacuum chamber to conduct tests to compare the effects of the atmosphere on corrosion and redeposition of material during the interaction process. This turned out to not be possible due to conflicts in laboratory availability. The samples from this second set of tests were then processed similarly to the first group.

**Set Up and Operation of the Experiment**

The second set of experiments utilized a 12 kW IPG fiber laser located in ARL facilities in research west on the Penn State University Park campus. The laser was controlled from a secure control room in which the test was visible through protective glass. The testing area was easily accessible which facilitated the changing of the sample pieces. These samples were placed on a work table below the laser. The top surface was at a slight angle to the path of propagation of the laser to prevent damage to the optics from reflection. The laser was controlled by the ARL staff member, Jay Tressler.

In each run of the experiment, a sample of material was placed below the laser on the flat work table. Spot size was measured with a ruler and visual inspection of a targeting laser that
was eye safe. When necessary the spot size was adjusted by changing the vertical distance to the laser from the surface of the sample. The power was chosen to provide an appropriate intensity at the surface of the material sample. Spot sizes and power levels were varied in order to acquire measurements for several different laser intensities acting on the surface. Exposure time was determined based on previous runs. The decision was based on the resulting surface features already created for that material at that intensity level. If there was very little interaction the exposure time was increased and if there was a large surface feature or one that experienced melt flow or ejection the exposure time was decreased. An exposure time of one second was used as a standard starting place when testing a material for the first time at a new intensity level. After irradiating a sample, it was removed with pliers and marked with a number for identification. Samples were stored and sorted for measurement with the optical profilometer.

Conditions of the Experiment

The purpose of this series of tests was to measure the evaporation rate of additional materials as well as decrease the material removed via melt flow and ejection. The effects of melt flow and ejection were minimized by decreasing the intensity of the laser and the time the samples were exposed to the laser relative to the conditions in the first experiment. The laser intensity was controlled by changing the power delivered by the laser and changing the spot size on the surface of the sample. These two conditions were changed such that each material was exposed to several intensities. The exposure time was kept at 1 second or below for most tests to decrease the amount of material that became liquid upon reaching the melting temperature. This also decreased the time in which molten material could flow before cooling and becoming solid again. These changes from the first experiment resulted in improved measurements.
The power levels used in this experiment were varied between 7.6 kW at the highest setting and 2.8 kW at the lowest setting. The spot sizes ranged from 15 mm to 27 mm in diameter. Combining different combinations of power levels and spot sizes resulted in several laser intensities. The lowest intensity tested with was 0.57 kW/cm². The highest intensity was 4.3 kW/cm². The time at which most samples were exposed was kept near 1 second or below although a couple measurements were made for exposure times of up to 2.5 seconds for the low intensity runs.

These conditions in the second experiment were successful in decreasing the effects of melt flow and ejection. This became apparent during the analysis and measurement of the tested material samples. The data collected in experiments one and two have been processed and analyzed in Chapter 3.
Chapter 3

Results and Analysis of Laser-Matter Interaction Experiments

Outline of Experimental Results

The laser-matter interaction experiments consisted of exposing different materials to a high energy laser at varying degrees of intensity and measuring surface temperatures along with maximum depth and surface features using optical profilometry. The measurements taken using optical profilometry were used to calculate the evaporation rate for a given sample of material that had been acted upon by the high energy laser.

It is useful to compare the evaporation rates found to the intensities of the high energy laser as well as the surface temperatures. According to theory, the evaporation rate is a function of the temperature at the surface of the material. By plotting the evaporation rate as a function of laser intensity and surface temperature it allows for the understanding of how the evaporation rate changes with respect to these independent quantities. The theoretical model under development at the Applied Research Laboratory at Penn State will be compared to these results to determine the accuracy of its prediction of transient evaporation.

Results of the First Experimental Data Set

Calculation of Evaporation Rate

The use of optical profilometry allows for the calculation of the evaporation rate for each tested sample of material. This technique images and measures the features on the surface of the
material. The point of maximum depth indicates the point of maximum evaporation; therefore, this was measured for each sample.

As seen in Chapter 1, the evaporation rate is a function of the number of particles determined by the distribution function, the velocity and mass of the particles, and the density of the material. These quantities multiplied together give the evaporation rate in units of mass per unit area per unit time. This can be seen in Equation 12 below.

\[ J = n m \sqrt{\frac{m}{2\pi kT}} \int v_x e^{-\frac{mv_x^2}{2kT}} dv_x \]  

(12)

The evaporation rate can be found by determining maximum removal velocity of the high energy laser. The removal velocity is found by measuring the maximum depth of the surface feature of a sample and dividing by the exposure time. This velocity can be multiplied by the density of the material at its melting point to get the experimentally measured maximum evaporation rate. Equation 13 illustrates this relationship.

\[ J = \rho_{\text{melting point}} v_{\text{max}} \]  

(13)

For a high energy laser intensity the maximum depth of the evaporated zone can be plotted as a function of the exposure time. The maximum depth divided by the exposure time yields the maximum removal velocity of that sample. The removal velocity is the slope of the trend lines in the plots of maximum depth plotted against exposure time. The maximum depth of the samples plotted against the exposure time can be found in Figures 3-1 and 3-2 separated into different data sets by laser intensity.
**Aluminum Maximum Depth of Evaporation Zone**

![Graph showing Maximum Penetrative Depth of the Evaporation Zone in Aluminum](image)

*Figure 3-1 Maximum Penetrative Depth of the Evaporation Zone in Aluminum*

**Iron Maximum Depth of Evaporation Zone**

![Graph showing Maximum Penetrative Depth of the Evaporation Zone in Iron](image)

*Figure 3-2 Maximum Penetrative Depth of the Evaporation Zone in Iron*
Surface Features

Examining the features of the surface of the material following exposure to the laser is important to understanding what was occurring during the process of interaction. The optical profilometer images the surface of the material. From the imaging one cannot only measure distances but also create two and three dimensional images. The images can be viewed from any angle and across a wide range of zoom levels. The view on this small scale aids in the understanding of the laser interaction process.

Below one can see examples of the images. Figures 3-3 and 3-4 are two and three dimensional views of a sample of aluminum. Figures 3-5 and 3-6 are two and three dimensional views of a sample of iron.

Figure 3-3 2-D plot of an Aluminum Sample after Laser Interaction
Figure 3-4 3-D Image of Aluminum after Laser Interaction

Figure 3-5 2-D image of Iron after Laser Interaction
An interpolating algorithm is applied to the data collected by the profilometer in order to fill in gaps between data points. Gaps between data points occur due to sharp angles on the surface and poor reflectivity. Figures 3-3 through 3-6 are images after the data has been interpolated.

When examining the images one can see the approximately flat plane that is outside of the effected evaporation zone. The crater in the pictures is a result of the laser-matter interaction process in which matter is lost or moved due to transient evaporation, thermal expansion, melt push and even ejection in some cases.

Near the outside edge of the effected zone the material is often seen to be raised above the original flat plane. This is likely a combination of many factors. Thermal expansion of the material as it heats up in the center will cause molten material to be pushed outward. In some cases there is enough recoil pressure to cause flow of molten material to the outside edges. This can even result in ejection of molten material from the surface. In the case of molten material ejection, the evaporated material cannot be distinguished from that which was ejected. This may

Figure 3-6 3-D Image of Iron after Laser Interaction
also be to some extent the result of condensation of evaporated atoms that have returned to the surface after having made collisions with air molecules. Corrosion resulting from interaction with gasses in the air may also be a contributing factor.

At the center of the crater it can be seen that the surface drops below the original plane. The material missing from this region either evaporated, was ejected, or was pushed outward. The center is the region of highest intensity which will correspond to the region experiencing the highest rate of evaporation and thus result in the maximum penetrative depth.

Another useful feature of the profilometry software is the ability to measure profile depths across the surface and plot them. This was useful for determining the maximum depth of the feature and examining how the surface changed in depth across the diameter of the crater. Figures 3-7 and 3-8 are examples of profile depth plots from the same aluminum and iron samples show in Figures 3-3 through 3-6.

![Figure 3-7 Profile Plot of the Surface Height of Aluminum Sample](image)
Melt Flow and Ejection

The flow or ejection of molten material at the surface of the metal that has experienced thermal energy increasing to such an extent that some of the material is in a liquid (molten) state is a process caused by the recoil force of evaporating atoms from the surface of the metal. It is not possible to distinguish between what melt has evaporated and what has been ejected or pushed outward. For this reason, such samples were plotted separately for evaporation rate and used to get a sense of the range of error melt flow and ejection can cause.

The effect of melt flow will increase as exposure time increases. Once the molten material begins to experience the recoil force the melt will begin to flow away from the center or in the extreme case be ejected if the recoil force is high. The flow will approach a steady state as the exposure time grows. Another contributing factor is laser intensity. Large intensities cause greater evaporation and thus recoil force. Lower intensities can be used to avoid material ejection and increase the time needed to result in melt flow. One can decrease the amount of melt flow by
decreasing the exposure time in which the recoil force is not applied long enough to result in significant flow of molten material.

When melt flow takes place material is forced outward from the center of the beam. This creates a larger empty space than would have occurred just from evaporation. If the material is heated long enough there will take a significant amount of time for the molten material to once again become solid. During this time the molten material can flow back into the empty crater created during the laser-matter interaction. The flow outward and inward decrease the accuracy that can be achieved in measuring the evaporation at the center of the beam. These effects must be prevented to achieve satisfactory evaporation measurements. Figure 3-9 displays drawings of the melt flow process. The top drawing shows the ideal crater that is only the result of evaporation. The middle drawing indicates the flow of molten material outward. The bottom or third drawing shows the flow of molten material back into the depression.

![Figure 3-9 Drawing of the Effect of Molten Material Flow](image)
The observations made visually, with the profilometer, and with the infrared video of the surface are important to understanding the laser-matter interaction and for identifying melt flow and ejection. When measuring the transient evaporation, samples that experienced melt ejection or had melt flow to the outside edges were grouped separately in the plots of evaporation rate.

Limited visual observations were made during the experiment. The control room was separate from the lab containing the laser and the experiment but a window allowed visual access. From the control room one could see the laser interact with the sample at a distance. The test was often very bright. This made visual observations more difficult. In some instances, individuals in the lab control room did observe melt ejection or “sparking” during some tests. This usually occurred at higher intensities and was recorded along with the other data.

The profilometer allowed observations to be made on a very small scale. The characteristics of the surface features, which were discussed earlier, are an indication of the interaction process. The extra material at the outside of the crater is a subject that is explored further in the second set of tests.

The infrared video taken of the surface has been an especially valuable tool for observing the interaction of the high energy laser with the metal samples. The video allows one to see how the temperature changes on the surface during the test. The progression of the heat affected zone can be seen. The temperatures at different points can be measured. The viewer can also see melt being pushed to the edges in some cases. When this happens the hottest areas can be seen to move outward. Melt ejection can also be seen in the infrared videos. The heat signature of the ejected matter can be seen on the video. These videos were helpful in identifying samples that experienced melt push or ejection. Figure 3-10 displays a screen shot from an infrared video.
The process of evaporation is an important effect of interaction with a high energy laser. The rate at which material is removed from the surface of an object is a critical process that effects applications of high energy lasers. Understanding how material is removed and at what rate will allow for improved modeling of the process. Improved analytical models of laser-matter interaction will provide predictions that will more exactly match that seen in experiments and industry.

The evaporation rate has been calculated for the samples exposed to different intensities of a high power laser. As explained earlier, the maximum depth was measured using a profilometer. The maximum depth was then divided by the exposure time to yield the removal velocity. This removal velocity is multiplied by the density of the material to give the rate of evaporation. The two most important quantities to compare this to are the intensity of the laser on
the surface and the surface temperature. The intensity of the laser determines the amount of energy being transferred to the material. Surface temperature is related to the energy of the molecules which is dependent upon the laser intensity. Energy transfer due to the laser raises the temperature which determines the rate of evaporation. The analytical model indicates that evaporation rate is a function of surface temperature as expected.

The plots of the evaporation rates of aluminum and iron are presented in the figures below to better understand how it changes with energy input from the laser. The evaporation rates were plotted against the laser intensity as well as the surface temperature. Figures 3-11 and 3-12 contain these plots which are especially useful for understanding the transient evaporation process.

**Average Evaporation Rate vs. Intensity**

![Graph showing average evaporation rate vs. intensity for aluminum, iron, questionable aluminum data, and questionable iron data.](image)

*Figure 3-11 Average Evaporation Rate vs. Intensity*
The evaporation rate for samples exposed to the same level of laser intensity were averaged together to make it easier to see how the evaporation rate changes as the laser intensity is adjusted. Examining Figure 3-11, one can see a somewhat linear increase in the average rate of evaporation as laser intensity increases. This is the expected trend predicted by the new theory. Also plotted are data points that, while measured, do not represent the evaporation rate well. The data points labeled as questionable identify measurements made on samples that are known to have experienced the effect of melt flow or ejection but are still plotted for comparison. The flow of the melt distorts the measurement of the maximum evaporation depth which then skews the calculation of evaporation rate. This is also present to some extent in the non-questionable data. Theoretically one should find the same evaporation rate for all samples of the same material exposed to the same high energy laser intensity. Samples that experienced small amounts of melt flow were averaged together to provide an idea of the correct evaporation rate. The second set of planned experiments will expose materials over much shorter times such that melt flow does not occur in any significant way and evaporation rates can be found at a much higher accuracy. It is interesting to compare the questionable data to examine the differences in the rate of material removed from the surface of the sample.

Figure 3-12 shown below is a plot of the evaporation rate against the surface temperature. Theory shows that the evaporation rate is a function of the surface temperature. This makes this plot especially valuable for understanding the transient evaporation process and how it compares to existing theory.
Individual evaporation rates for tested samples are plotted against the maximum surface temperature of the metal sample in Figure 3-12. The maximum surface temperature was found using an infrared camera. When viewing the recording, the highest temperature was typically found at the center of the spot created by the laser. The trend of aluminum can be seen to increase linearly as a function of surface temperature. The rates for the questionable aluminum data are a bit low. This is likely a result of melt flow on the sample and was especially a problem for samples exposed for longer periods of time. Iron displays a wide range of evaporation rates over a small range of surface temperatures. The effects of melt flow and melt ejection were more pronounced with iron and resulted in a wider range of measured values and decreased accuracy. The questionable iron measurements are likely due to the melt flow. There were several cases of melt ejection which resulted in the very high measurements seen on the plot. A few of the
measurements that are high, but not marked questionable, likely experienced melt eject even though it was not seen. One can see; however, a linear trend of the evaporation rate of iron among the more reasonable measurements. The accuracy increased and the rate was better represented by data in the second set of experiments. The exposure times were shortened significantly in order to avoid the melt flow and ejection issue.

The solution for the Hertz-Knudsen equation was also plotted in Figure 3-12 to compare with experimental measurements. The Hertz-Knudsen solution was found using a coefficient of evaporation of 1 and a coefficient of condensation of 0. This results in the maximum evaporation rate that the Hurtz-Knudsen equation will predict. One can see in the graph that the solution is relatively low and doesn’t rise significantly until much higher temperatures. It is much lower than the experimental measurements for both aluminum and iron. The experimental measurements correlate with the analytical model, under development at ARL, which predicts a linear increase in the evaporation rate. This is in contrast to the curved solution of Hertz-Knudsen that rapidly increases at high temperatures. The magnitude of the Hertz-Knudsen solution is also much lower than the values observed experimentally, especially for lower temperatures.

It is also of interest to plot the maximum surface temperature measured by the infrared camera against the intensity of the laser. This provides an idea of the conditions on the surface of the material while interacting with the laser. As the laser interacts with the surface the temperature of the material will climb rapidly and level off at some maximum temperature. This is of interest in determining whether the material reached its boiling temperature or if it reached a temperature at which the material properties changed. This plot is given in Figure 3-13.
One can see an approximately linear increase of the maximum surface temperature in Figure 3-13 with the laser intensity. This increase is expected since the increase in laser intensity corresponds to an increase in energy transferred to the surface of the material. The rather low aluminum data point at 25,000 W/cm$^2$ may be a result of increased cooling due to melt ejection or possible flow or possibly was not exposed long enough to reach a steady state max temperature.

These discrepancies between experimental measurements and Hertz-Knudsen indicate the need for an improved theory. The theory under development at ARL will predict the linear trend of evaporation rate as a function of surface temperature. This new theory will be far more accurate in its predicted values. The measurements made during these series of experiments as well as the new theory will improve understanding of transient evaporation that occurs during the
interaction of a high energy laser with matter. It will also allow realistic predictions of the process to be made.

In the second set of experiments the data quality was improved. The experiments were conducted over a wider range of laser intensities that were lower than in the first experiment and more materials were tested. The samples were exposed over much shorter time ranges in order to avoid the effects of melt flow and ejection. This data provided improved measurements of the evaporation rate.

Results of the Second Experiment

During the second experiment the goal was to decrease the effect of melt flow and ejection on the measurement of mass removal rate and to test additional materials. Aluminum and iron were measured again. Aluminum alloy 1100 was used, which is 99% pure aluminum. Nickel, Inconel 625, and zinc were added during the second experiment. The flow along with ejection of molten material was decreased by testing at lower laser intensities and over short, in the vicinity of one second, exposure times. This greatly decreased the affect of this on the measurement of the mass removal rate from the surface. Nickel was an exception. It was prone to material ejection during the tests even though lower intensities and exposure times were used. Nickel appeared to transition between no measurable surface interaction to ejection of material. Tests were not able to be conducted in which nickel did not experience melt ejection but also experienced measurable evaporation. For this reasons the nickel samples were not measured and are not analyzed further in this analysis. The decreased effect of melt flow was seen in the analysis of the other material samples following the experiment. The measurement of the evaporation rates are more accurate and better show the trends expected by the theory under development at the Applied Research Lab.
**Profilometer Examination**

As was the case in the first experiment, the samples of material irradiated by the laser during the second experiment were analyzed and measured with an optical profilometer. The profilometer was used to image and examine the surface as well as measure the maximum depth of the surface feature. In particular, the samples were examined for signs of melt flow. The amount of material at the edge of the surface feature that was raised above the surface that did not interact with the laser is a good indication of the effect of melt flow. Surface features such as small holes were indicative of melt ejection. The analysis showed that the flow or ejection of molten material was greatly decreased as compared with the first experiment. This can be seen in one of the 3-D images and profile depth plots displayed in Figures 3-14 and 3-15.

![3D Plot of an Inconel Sample](image)

**Figure 3-14** 3-D Plot of an Inconel Sample
One can see in the three dimensional plot of the surface in Figure 3-14 that material has not been significantly pushed upward by melt flow. The feature slopes upward toward the surface that did not interact with the laser at the edges of the feature. The profile plot shows that the feature does not rise above this plane. One can also see characteristics in the surface features resulting from the shape of the laser. The laser was not a perfect Gaussian distribution, similar to the first experiment. Uneven intensity peaks near the center of the beam caused a similar pattern to be observed in the surface features of the tested materials. A relatively low intensity point near the center of the beam is thought to have resulted in a raised “bump” that occurred in the deep center regions of many of the samples. This “bump” is present in these two figures.

Profile plots such as the one seen in Figure 3-15 were used to determine the maximum depth of the feature. The maximum depth corresponds to the maximum rate of mass removal. This measurement is used to calculate the mass removal/evaporation rate as was explained earlier in this chapter. The depths measured have been plotted against the time over which the samples
were exposed. Each level of laser intensity is plotted as a separate data series. These plots have been included in Figures 3-16, 3-17, 3-18, and 3-19.

**Figure 3-16** Maximum Depth of Aluminum Samples Plotted Against Exposure Time

- Blue diamonds: Intensity of 4.3 kW/cm²
- Red squares: Intensity of 3.17 kW/cm²
- Green triangles: Intensity of 2.42 kW/cm²
Maximum Depth of Iron Samples vs. Exposure Time

- Intensity of 1.78 kW/cm²
- Intensity of 1.5 kW/cm²
- Intensity of .76 kW/cm²

Figure 3-17 Maximum Depth of Iron Samples Plotted Against Exposure Time

Maximum Depth of Inconel Samples vs. Exposure Time

- Intensity of .82 kW/cm²
- Intensity of 1 kW/cm²
- Intensity of 1.81 kW/cm²
- Intensity of 2.42 kW/cm²

Figure 3-18 Maximum Depth of Inconel Plotted Against Exposure Time
Examining these four plots is useful in that the maximum depth measurement will show similar trends as that expected of the evaporation rate. One can see by examining these plots that there is a linear trend as the maximum depth measured with the profilometer increases with exposure time for particular laser intensities. This is most easily seen in the maximum depth plots of Inconel and zinc. It is most difficult to see in the iron plot. Iron was the most prone to melt flow and ejection. These processes have a much great impact on the iron measurements and this is evident in examining the maximum measured depths of iron. One can also see that, as expected, tests run at lower intensities took longer to penetrate into the sample. The trend lines of the lower intensity data series are shifted to the right of the higher intensity data series. The trends in these plots also indicate a linear increase in the evaporation rate as the surface temperature increases. The higher intensities result in higher surface temperatures and thus a larger evaporation rate and faster material removal from the surface.
Data Analysis of the Second Experiment

The maximum depths of the surface features measured with the profilometer are used to calculate the evaporation rates of the materials. This can also be referred to as the mass removal rate since this measurement also includes the effects of other forms of mass removal. It is useful to examine how the evaporation rate changes as the laser intensity changes. As the intensity changes so does the temperature of the material. The evaporation rate is a function of the surface temperature; therefore, it is also important to compare the evaporation rates to the surface temperature as well. The trends of the experimentally measured evaporation rates can be studied and compared to the trends expected by the theory under development at ARL. In the future, these measurements can be compared to the specific predictions made by this theory following its completion.

The evaporation rate can be plotted against the laser intensity to determine the correlation between the two. The laser intensity corresponds to the energy being transferred to the surface. As the intensity increases the energy transfer increases. This will raise the temperature of the surface. The evaporation rate is known from theory to be a function of the surface temperature and will increase as the temperature increases and therefore as the intensity increases. The preliminary predictions of the developing theory at ARL show that the evaporation rate will increase linearly with the laser intensity and surface temperature. The evaporation rates measured in the tests making up the second experiment are plotted against the intensity of the laser in Figure 3-20.
The trends in the plot in Figure 3-20 can easily be seen. All four metals show a linear correlation between the evaporation rate and laser intensity. The evaporation rates of each material can be seen to increase linearly as the laser intensity increases. The multiple evaporation rates measured at the same intensity indicate samples that were exposed for different lengths of time. Those exposed for longer time frames would have reached higher surface temperatures and therefore higher evaporation rates. It is interesting to note that different materials show different rates at which the evaporation rate will increase as the laser intensity increases. The trend of the aluminum data points can be seen to have a rather low slope where as the zinc increases far more rapidly. The evaporation rate is expected by developing theory to behave linearly. This plot matches what is expected from theoretical studies and preliminary theoretical predictions.
In the first experiment infrared video was used to measure the maximum surface temperature experience by each sample. Infrared video equipment was not available for the second experiment. It is, however, important to compare the experimental evaporation rates with that of the surface temperature. In order to do this it was determined that the maximum surface temperature must be calculated since a means of measuring it was not available. An equation for the surface temperature that is a function of laser intensity, surface reflectivity, thermal diffusivity, and thermal conductivity was used to calculate the surface temperature. This equation can be found in a publication by Rosenthal in the Transactions of the ASME journal (10). The is given as Equation 14.

$$T = \left( \frac{2I_0(1 - r)}{\kappa} \right) \sqrt{\alpha t} + T_0$$

(14)

The term $T_0$ in the above equation represents the reference temperature. In this case, it was 273 K. This equation was used to calculate the maximum surface temperature the samples experienced during testing. Table 3 shows the values of the constants used in Equation 14.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity, $\kappa$, W/m-K</th>
<th>Thermal Diffusivity, $\alpha$, m²/s</th>
<th>Reflectivity, $r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>237</td>
<td>8.42 * 10⁻⁵</td>
<td>.5</td>
</tr>
<tr>
<td>Iron</td>
<td>80.4</td>
<td>2.3 * 10⁻⁵</td>
<td>.3</td>
</tr>
<tr>
<td>Inconel</td>
<td>14.54</td>
<td>3.43 * 10⁻⁶</td>
<td>.4</td>
</tr>
<tr>
<td>Zinc</td>
<td>116</td>
<td>4.31 * 10⁻⁵</td>
<td>.5</td>
</tr>
</tbody>
</table>
It is important to look at the trend in how the maximum surface temperature changed with exposure time for a given laser intensity. Figures 3-21, 3-22, 3-23, 3-24 show this relationship. In these plots the maximum surface temperatures calculated with Equation 14 are plotted against the exposure time for each intensity.

**Calculated Maximum Temperature vs. Exposure Time for Aluminum**

- Intensity of 4.3 kW/cm²
- Intensity of 3.12 kW/cm²
- Intensity of 2.42 kW/cm²

*Figure 3-21 Maximum Surface Temperature vs. Exposure Time for Aluminum*
**Calculated Maximum Temperature vs. Exposure Time for Iron**

![Graph 1](image1)

*Figure 3-22 Maximum Surface Temperature Calculated for Iron vs. Exposure Time*

**Calculated Maximum Temperature vs. Exposure Time for Inconel 625**

![Graph 2](image2)

*Figure 3-23 Maximum Calculated Surface Temperature for Inconel 625 vs. Exposure Time*
Figures 3-21 through 3-24 show the relationship between the maximum surface temperature that was found using Equation 14. The surface temperature of a surface being heated by a high energy laser will increase rapidly at first. As time increases the slope of the temperature line will decrease. The surface temperature, for particular laser intensities, will approach a steady state value. This steady state value will increase with laser intensity. As laser intensity continues to increase the steady state temperature will approach that of the boiling point of the material. One can examine the previous four plots and see this trend. In the plots, separate values of intensity are plotted as separate data series. The data points, for each intensity, form a curve that follows the expected behavior of the surface temperature. Most of the data points lie on the curve between the most rapidly increasing portion and the portion relatively close to the asymptote.
These plots give important insight into the measured values of the evaporation rate. The evaporation rate is a function of the surface temperature. One can see that the surface temperature changes rapidly until it levels off at the steady state temperature. This indicates that the evaporation rate will initially increase rapidly and approach a steady state mass removal rate as time increases. The evaporation rates measured in the experiments are an average of the rate of mass removal that took place over the range of time in which the surface temperature increased, approached a steady state, and then decreased following the deactivation of the laser. The actual evaporation rate at a specified temperature will be larger than that which was measured. As time increases this error decreases; however, the effects of melt flow and ejection increase with time. These measurements fall in between these effects to minimize both. Future work will include integration while making use of this temperature equation that is a function of time to improve the prediction and modeling of the surface temperature and evaporation rate. This temperature function of time will also be used in the Hertz-Knudsen equation to improve its predictions.

The measured average evaporation rates discussed in the previous paragraph have been plotted against the maximum surface temperature found using Equation 14. The trend of the evaporation rate as a function of maximum surface temperature is important to examine. There will be some error resulting from the fact that the measured evaporation rates are an average. The maximum evaporation rate at the specified temperature will be higher. The average rates that were measured include the average over the time frame in which the temperature at the surface grew rapidly, approached a steady state, and decreased after the laser was deactivated. This plot remains useful, however, in examining how the evaporation rate changes with surface temperature. These measurements will be useful for comparison to theoretical predictions that will be made in the future by the developing theory at ARL. The plot of measured average
evaporation rate plotted against the maximum calculated surface temperature is included in Figure 3-25.

![Graph: Average Evaporation Rate vs. Calculated Maximum Surface Temperature](image)

In Figure 3-25 one can see the experimentally measured average evaporation rates plotted against the maximum surface temperature. Also plotted are the predictions made by the Hertz-Knudsen equation. The Hertz-Knudsen predictions are made for an evaporation coefficient of one and a condensation coefficient of zero. This is the maximum prediction made by the Hertz-Knudsen equation. Only the predictions of the Hertz-Knudsen equation for aluminum and iron are plotted. The prediction for zinc was very high and far beyond the y-axis range. The calculation was not able to be preformed for Inconel do to unknown and difficult to calculate material properties of the alloy.
As in the first experiment, the predictions made by the Hertz-Knudsen equation for iron and aluminum are far too low when compared with the experimental measurements. This shows a need for a more accurate analytical method of prediction. The evaporation rates of zinc increase rapidly as compared with the other tested materials. The Hertz-Knudsen equation overpredicts this, further demonstrating a need for an improved analytical model.

Examining the evaporation rates of each material, one can see that they all show a linear trend. The evaporation rates increase linearly with the surface temperature. This trend is expected from the preliminary results of the developing analytical model under development at ARL. Of these four metals, the evaporation rate of zinc increases the most rapidly while Inconel and iron have similar evaporation rates that increase at a lower rate with temperature than that of zinc. Aluminum appears to have a slightly lower rate of increase of evaporation rate with surface temperature.

The linear increase of the evaporation rates with surface temperature has been initially predicted by the new analytical model. Once the model is finished, it is expected that its predictions will be validated by the data collected during these experiments. This new model will be valuable in understanding the transient evaporation process that occurs during high energy laser interaction with matter.
Chapter 4

Discussion and Path Forward

The goal of this project was to experimentally measure the rate of evaporation of multiple materials and compare the experimental measurements to analytical equations under development at the Applied Research Laboratory at the Pennsylvania State University. The evaporation rates (which include some amount of error due to other mass transfer processes and changing surface temperatures) were measured for aluminum, iron, Inconel 625, and zinc. These measurements were compared to preliminary predictions made by the developing analytical equations. At the time of publication of this thesis, these equations have not yet been completed. In the future, the analytical equations will be used to generate predictions of evaporation rate. These analytical predictions will be compared to those measured experimentally. The predictions of the analytical equations are also planned to be compared to experimental measurements of evaporation rate occurring in a supersonic flow. This will investigate the effect of evaporation on the boundary layer and the interaction between convective cooling and the evaporation rate. The comparison of the analytical theory to these measurements will be used to further validate the theory.

Conclusions

In this endeavor, the average rates of evaporation induced by interaction with a high energy laser were measured and analyzed. The evaporation rates were compared with laser intensity at the surface and with the maximum temperature at that surface. The interaction process and the results were also closely studied. The trends seen in how the evaporation rate changes as a function of laser intensity and surface temperature match the preliminary predictions
of the new analytical model currently under development at the Applied Research Laboratory at Penn State at the time of publication of this thesis. These measurements will be especially useful for validation of this analytical model in the future.

The new analytical model, after having completed the analysis of these experiments, is expected to accurately model the transient evaporation process. The author anticipates that the data collected in these experiments will validate the predictions that will be made by the new analytical equations. This new model will be valuable in modeling and predicting the effects of high energy laser-matter interaction. Many applications of high energy lasers such as directed energy weapons, laser welding, and combustion will benefit from this model. Future tests are expected to further validate this new analytical model.

**Path Forward for Experimental Investigation**

The experiments conducted so far have measured the evaporation rate for several different materials at multiple levels of intensity and exposure time. These tests were conducted in standard atmospheric conditions with no flow of air across the surface of the material that is interacting with the laser. These experimental measurements will be used to verify the new theoretical equations under development at the Applied Research Laboratory at Penn State. A second phase of the project is in planning to experimentally measure the evaporation rate in a high velocity flow and compare these measurements to the predictions made by the new theory.

Measuring the rate of evaporation of different metals in a high velocity flow is an important part of continuing this project. Many applications of high power lasers do not operate in static atmosphere environments. For instance, the lethality of directed energy weapons being used as a method of missile defense is strongly affected by high velocity cross flows. In this application, the high energy laser targets a ballistic missile shortly after launch or somewhere in
flight when there is high velocity flow across the surface of the missile. The cross flow provides significant cooling which directly affects the energy needed to make the laser lethal. This subject also applies to other areas in which high energy lasers are used. One such application that is currently being studied by various research projects is laser ablation propulsion. This is a form of propulsion in which the laser ablates a material that, when ablated, is ejected from the surface and provides thrust. In this process there is a significant flow across the surface that will impact the energy required for the laser. To better understand and apply the new developing theory to these applications, the evaporation process must be measured in high velocity flows and compared with theoretical predictions.

Currently, at the time this thesis is published, a wind tunnel is undergoing a modification to provide the capability to generate flows above Mach one. The laser-matter interaction will be conducted in the supersonic flow to observe the strong effect that will result from such a high velocity flow. The wind tunnel is being modified to mount the materials as well. The mounting is being designed to prevent the formation of shock waves by making the samples of material flush with the wall of the wind tunnel. Planning is underway to get access to the necessary equipment and supplies while the wind tunnel modification is completed.

The materials tested in the first phase of the project will also be used to measure the evaporation rate in a supersonic flow. They will again be exposed to various laser intensities for varying lengths of time. Additional materials may be tested in the future as needed. The sample pieces will be mounted such that they are flush with the wall of the tunnel and do not cause shock waves or separated flow to form. The flow needs to remain attached to provide the maximum rate of cooling. The laser will shine through a window in the tunnel. All laser equipment will be placed outside the tunnel walls to avoid interaction with the supersonic flow of air.

The flow across the surface of the material will result in significant convective cooling of the material. This will decrease the effect of the high energy laser. The energy removed by the
air flow will decrease the rate of evaporation from the surface. As the energy delivered by the laser is increased the rate of evaporation will increase. This means the flux of atoms or molecules being removed from the surface will grow. The evaporating atoms will interact with the boundary layer of the flow. As evaporation continues to increase, the boundary layer will begin to rise above the surface. This process reduces the rate of convective cooling of the surface. When the boundary layer becomes raised significantly above the material the rate of cooling will approach zero. At this point there will be a runaway effect of evaporation. This is the critical point at which the laser becomes the most lethal. It will induce the maximum rate of evaporation possible which will be a function of the intensity and material properties.

In this phase of the project, we wish to identify the approximate point at which critical lethal effectiveness of the laser occurs while in a supersonic flow. Laser intensities will be adjusted to measure this effect. The measurements of evaporation rate will also be compared to those predicted by the new theory currently under development at ARL. This comparison will be useful in determining the accuracy of the new theoretical equations and if necessary improving upon them. The information gathered in these future experiments will be valuable to improving the theoretical predictions and understanding of transient evaporation resulting from high energy laser-matter interaction.

These future tests are expected to further validate the developing analytical model. The tests to date match the expected trends. This new analytical model is expected to develop into a valuable tool for predicting the transient evaporation process. This model will benefit the modeling and predictions of high energy laser applications such as directed energy weapons, laser welding, and combustion. The new analytical equations are expected to generate an improved understanding of the transient evaporation that occurs during the laser-matter interaction process.
Bibliography


