A Study of the Effects of Turning Angle on Particle Deposition in Gas Turbine Combustor Liner Effusion Cooling Holes

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

Rory Alexander Fabian Blunt B.A. B.S.

Graduate Program in Mechanical Engineering

The Ohio State University

2016

Master's Examination Committee:

Dr. Jeffery Bons, Advisor

Dr. Randall Mathison
Abstract

The deposition of particulate in gas turbine cooling systems with a focus on single wall effusion holes was investigated. This study focused on the effect that flow turning angle into the cooling hole has on the blockage of these holes. The test hardware is based on a single walled combustor liner with angled effusion holes. By allowing the mass flow through the test system to decrease as deposition occurred the pressure drop across the test coupon was held at 3% of the discharge pressure. The mean flow turning angle was varied between favorable (10°) and adverse (130°) by mounting the plate in different orientations on a stalled plenum. The dust used was 0-10 μm Arizona Road Dust (ARD). These tests were run with a coupon temperature of 870 °C; this was achieved by use of an electric kiln. Flow reduction of the adverse test plates was around twice as much as the favorable condition; however both conditions had very similar capture efficiencies. 3D scans and sectioned test plates were used to investigate the different structures of the deposition that formed on the test plates and in the effusion holes. It is seen that turning angle does not influence the amount of captured mass but just the location of where that mass is captured and so its effect on the flow.

A companion CFD study was also performed to explore the ability of computational models to predict the impact location and deposition depending on the impingement angle. This model was a simplified case and modeled a single effusion hole with the same geometry as the test plate. The inlet conditions were held constant and
based on the experimental data. Particles were tracked with an Eulerian-Lagrangian method and it was seen that the predicted first impact locations closely matched the deposition seen in the experimental setup. Additionally a sticking model was used to predict deposition. It was seen that under the simulated conditions this model predicted deposition similar to the experimental results.
Dedication

My friends and family.
Acknowledgments

I would like to acknowledge Robin Prenter for teaching me Fluent™. I would also like to thank Alex Karpinski and Kyle Hipp for helping to edit this document. Next I would like to acknowledge my friends and family for keeping me sane. Lastly I would like to acknowledge my lab mates for their input through all the stages of research.
Vita

June 2010 ........................................... Cambridge School of Weston

May 2014 .................................................. B.A. Mathematics & B.S. Mechanical

   Engineering, University of Rochester

June 2014 to present ................................... Graduate Research Associate, Department

   of Mechanical Engineering, The Ohio State

   University

Fields of Study

   Major Field: Mechanical Engineering

   Specialization: Experimental Fluid Dynamics and Heat Transfer
# Table of Contents

Abstract........................................................................................................................................... ii  

Dedication....................................................................................................................................... iv  

Acknowledgments......................................................................................................................... v  

Vita................................................................................................................................................... vi  

List of Tables ...................................................................................................................................... x  

List of Figures ....................................................................................................................................... xi  

Nomenclature....................................................................................................................................... xv  

Chapter 1: Introduction and Background........................................................................................ 1  

Past Studies ....................................................................................................................................... 2  

Chapter 2: Experimental Setup ........................................................................................................ 7  

Test Hardware ..................................................................................................................................... 7  

Test Facility......................................................................................................................................... 8  

Plenum............................................................................................................................................... 12  

Heating............................................................................................................................................... 20  

Feed System....................................................................................................................................... 21  

Particle Selection ............................................................................................................................ 23  

vii
IR Camera .................................................................................................................. 24
TemperatureCorrection .............................................................................................. 27
Test Procedure ........................................................................................................... 28
Post Test Procedure ................................................................................................. 31
Chapter 3: Computational Methods ............................................................................ 35
        Grid .................................................................................................................... 35
        Flow Solution .................................................................................................... 37
        Validation .......................................................................................................... 38
        Grid Independence ............................................................................................. 41
        Particle Injection ............................................................................................... 42
        Deposition and Impacts ..................................................................................... 43
Chapter 4: Results and Discussion ................................................................................ 45
        Experimental Results ......................................................................................... 45
          Favorable vs. Adverse (Directional Tests) ......................................................... 45
          Repeatability ..................................................................................................... 51
          Structures ......................................................................................................... 54
        CFD Results ........................................................................................................ 60
          Flow Solution .................................................................................................... 62
          Impact Locations and Deposition .................................................................... 65
Comparison ................................................................. 70
Small Particle Simulation .............................................. 73
Summary ......................................................................... 77
Chapter 5: Conclusion ..................................................... 78
Future Work .................................................................... 78
References ...................................................................... 80
Appendix A: Plenum Temperature Correction Code .................. 85
Appendix B: Experimental Test Log ..................................... 87
List of Tables

Table 1: Compiled Ash Compositions .......................................................... 24
Table 2: CFD Model Parameters ................................................................. 38
Table 3: Comparison of CFD and experimental Results .................................. 40
Table 4: Material Properties of ARD and Hastelloy ........................................ 43
Table 5: Experimental Test Conditions ........................................................ 45
Table 6: Mean Flow Check Percent Mass Flow Reduction from Post Test (0.5 – 2% BFM) and end of Deposition (3% BFM) .................................................. 48
Table 7: Values for plates shown in Figure 29 ................................................. 50
Table 8: Test Repeatability ............................................................................ 52
Table 9: Capture Efficiency ........................................................................... 54
List of Figures

Figure 1: Left) Dust Ingestion on Runway, Right) Ash Deposited on Turbine Vane (Casaday[2]).................................................................................................................. 1

Figure 2: Test Coupon ........................................................................................................ 7

Figure 3: Hole Layout Drawing (dimensions in mm)...................................................... 8

Figure 4: Experimental Facility Setup ........................................................................... 10

Figure 5: Particle Equilibration Analysis [14]............................................................... 11

Figure 6: Plenum ............................................................................................................ 13

Figure 7: Sample Plenum Velocity Distribution, Mean Favorable Turning Angle 10°, Mean Adverse Turning Angle 130° ................................................................. 13

Figure 8: PIV Setup ....................................................................................................... 15

Figure 9: Sample Flow Solution in the Plenum ............................................................ 16

Figure 10: Comparison of incoming flow angle at different flow speeds at y = 36 mm. ......................................................................................................................... 17

Figure 11: Velocity magnitude Contours for Different Plate Directions ................. 18

Figure 12: Comparison of Incoming Flow Angle with Different Plate Directions at y = 36 mm ............................................................................................................. 19

Figure 13: Turning Angle Diagram .............................................................................. 20

Figure 14: Particle Injection System ............................................................................ 22
Figure 15: Size distribution of 0-10 μm Arizona Road Dust (Powder Technology Incorporated\cite{26}) ................................................................. 23

Figure 16: Example IR Image in Digital Level ................................................................. 25

Figure 17: IR Calibration Curve ...................................................................................... 26

Figure 18: Plenum Temperature Schematic ..................................................................... 28

Figure 19: Sample Pre-Test Flow Curves ....................................................................... 30

Figure 20: Scanner Setup ............................................................................................... 32

Figure 21: Light Test Fixture .......................................................................................... 34

Figure 22: Grid Domain and Boundary Conditions a) BC shown on test plate, b) Domain ......................................................................................................................... 36

Figure 23: Areas of Averaged flow for CFD inlet conditions, 1) Low Speed, 2) Medium Speed, 3) High speed ................................................................................................. 37

Figure 24: Flow Entering an Effusion Hole a) Favorable b) Adverse, higher speed vectors in the hole have been clipped .................................................................................. 39

Figure 25: Flow Solution compared to Leylek and Zerkle\cite{34} ..................................... 41

Figure 26: Example time history of mass flow reduction for both plate configurations ............................................................................................................................ 46

Figure 27: Comparison of Post Flow Check for Different Turning Angles ............... 47

Figure 28: Complete Test area post Test, A) Favorable b) Adverse ............................. 48

Figure 29: light Test, A) Favorable, B) Reference, C) Adverse ................................. 49

Figure 30: Sectioned Effusion Holes, Top) Fully Blocked, Bottom) Partially Blocked ................................................................................................................................. 51

xii
Figure 31: Centerline Sweep of Starting IR images .................................................. 53

Figure 32: Repeatability Images, a) Favorable, b) Adverse ............................... 54

Figure 33: Structures on Favorable Test ................................................................. 55

Figure 34: Structures on an Adverse Test ............................................................... 56

Figure 35: Single Adverse Effusion Hole Under High Magnification ............. 57

Figure 36: Scans of tests in Figure 8 a) Favorable b) Adverse ..................... 58

Figure 37: Optical Profilometer Scan of a Favorable Test Section .............. 59

Figure 38: Optical Profilometer Scan of an Adverse Test Section .................. 60

Figure 39: Flow Entering an Effusion Hole a) Favorable b) Adverse, higher speed vectors in the hole have been clipped. $V_{in} = 2.05 \text{ m/s}$ .......................................................... 62

Figure 40: Flow Magnitude in Effusion Holes ......................................................... 63

Figure 41: Effect of Velocity on Flow Solution (Favorable) a) Inlet Velocity 2.84 m/s b) Inlet Velocity 1.91 m/s ................................................................. 64

Figure 42: Effect of Inlet Angle on Flow Solution (Favorable) a) Flow Angle $= 20^\circ$ b) Flow Angle $= 75^\circ$ ................................................................. 64

Figure 43: First Impact Locations (Red $\geq$ more than 15 impacts) a) Favorable b) Adverse ......................................................................................... 65

Figure 44: Multiple Impact Locations in Effusion Hole ....................................... 66

Figure 45: First impact Locations in 7.7% BFM, a) Favorable b) Adverse .......... 67

Figure 46: Histogram of Particle Deposition ......................................................... 68
Figure 47: Simulated Particle Deposition Colored by Particle Diameter. a) Favorable b) Adverse ................................................................. 69

Figure 48: Top View of Predicted Deposition Compared to Experimental Test in a Favorable Configuration (flow and holes go from Left to Right) ............................... 71

Figure 49: Top View of Predicted Deposition Compared to Experimental Test in an Adverse Configuration (flow goes Left to Right while, holes go Right to Left) .......... 72

Figure 50: Comparison of Deposition in Effusion Holes a) Favorable b) Adverse ................................................................................................................. 73

Figure 51: Histogram of Small Particle Deposition ............................................. 74

Figure 52: Small Particle Deposits Normalized by # of Impacts ....................... 75

Figure 53: Deposition of Small Particles a) Favorable b) Adverse ................. 76
Nomenclature

ARD  Arizona Road Dust
BFM  Back Flow Margin
PIV  Particle Image Velocimetry
P    Pressure
ρ    Density
T    Temperature
CE   Capture Efficiency
DL   Digital Level
m    Mass
ṁ    Mass Flow
U    Flow Velocity
θ    Impingement Angle
k    Thermal Conductivity
h    Heat Transfer Coefficient
l    Thickness or Length
OP   Optical Profilometer
St   Stokes Number
μ    Flow Viscosity
D    Hole Diameter
d   Particle Diameter

Subscripts

w   Plenum Wall
wi  Inside Edge of Plenum Wall
wo  outside Edge of Plenum Wall
f   Main Flow
c   Cold flow
h   Hot flow
Chapter 1: Introduction and Background

Gas turbines are being used more and more around the world both in the transportation industry as well as other roles, such as power generation. As these roles increase and diversify, turbines are being exposed to environments with poor air quality. The large amount of particles in this air can be harmful to turbine operation. Coal power turbines can ingest fly ash from the combustor, jet turbines can ingest particles while flying low over deserts or through smog clouds and volcanic ash clouds can seriously affect air travel. Dunn\cite{1} describes the real world effects that injected particles can have on a turbine.

Figure 1: Left) Dust Ingestion on Runway, Right) Ash Deposited on Turbine Vane (Casaday\cite{2})

The higher compression ratio a gas turbine operates at, the more thermodynamically efficient it is. These higher compression ratios however, result in
increased operating temperatures. This has been causing operating temperatures of combustors and turbines to increase for decades. Modern engines can run at temperatures above the softening points of the materials they are made of relying on techniques such as film and impingement cooling to operate. This cooling air is bled from the core flow in the compressor and can contain any contaminants the engine ingests. Because of the operating temperatures it is important to prevent any particle deposition, as it is likely to reduce the effectiveness of the cooling systems by blocking cooling paths. This can result in increased maintenance costs and downtime, as well as reduced operational periods.

Past Studies

The events and effects of an airliner flying through a volcanic ash cloud in 1982 are laid out by Dunn\textsuperscript{[1]}. In his paper Dunn reviews the damage done to the engine lays out the visual and instrumental warning signs of the danger, and ultimately describes procedures to avoid engine failure. Additionally dust particles with a mean diameter of 6 $\mu$m were found in the environmental control system (ECS). Like the cooling system the air for the ECS is bled off of the compressors. Presence of these particles suggests possible health issues in addition to those of damage to the engine. Events like this and the 2010 eruption of Eyjafjallajökull show why studies in deposition are so important.

Some deposition studies have been conducted on full-scale engines. In one such study the effects of a few contaminants, including volcanic ash were studied by Dunn \textit{et al.}\textsuperscript{[3]}. It was shown that as well as damaging the turbine and compressor blades, particle deposition can cause changes to the stall margin of the engine and rapid changes in the
burner pressure. Finally Dunn laid out a method to cycle the engine power allowing for the purge of some deposition provided the engine is not already compromised.

Kim et al.\cite{4} investigated deposition by using stripped down engines in a laboratory setting and seeding the intake air with volcanic ashes, sands or clay. Again it was found that particles are broken up in the compressor and typically exit with a mean diameter of less than 10 μm. It was shown that deposition is heavily influenced by the surface and flow temperatures and that the main mechanisms for damage to the engine were deposition on the turbine blades, erosion of the compressor blades and carbon build up in the combustor.

Research in the wide field of gas turbine deterioration is ongoing. Hamed and Tabakoff\cite{5} discusses and compares many prior studies: both experimental and computational. This summary focuses primarily on erosion and shows how and where damage, such as increased surface roughness to the blades, can occur. In computational studies Tabakoff and Hamed\cite{6} showed that damage due to erosion was highest on pressure sides of blades. Bons\cite{7} discusses the effects of deposition-increased surface roughness, noting the increased heat transfer and pressure losses that can occur. Bons goes on to discuss the loss of efficiency in cooling jets due to upstream deposition.

Since testing with complete engines can be extremely costly, major efforts have been put towards simulating the engine environment. Several high temperature wind tunnels have been built for this purpose. One such facility was used by Murphy et al.\cite{8,9} to deposit dust on turbine blades at 1100 C and 4 atm. The influence of several parameters such as blowing ratio and thermal coating were investigated. It was shown
that cooling the test coupon resulted in minimal deposition at all but the highest operating temperatures. This suggested that the thermal boundary layer and surface temperature play a major role in deposition.

In addition to the research carried out on general deposition trends for turbine blades, work has been done on studying the effects of dust in and around the cooling systems of an engine. The effects of slot cooling on an actual first stage turbine were investigated by Prenter et al.\cite{10}. It was found that there is a strong relation between coolant flow and deposition. The deposition around cooling holes was investigated by Ai et al.\cite{11}. They also showed that as the blowing ratio increases deposition in the cooling passages is reduced.

Many papers use test coupons manufactured to be representative of engine components with simplified geometries. Stewart\cite{12} used a flat plate with cooling hole to simulate the pressure side of a turbine blade. He found that deposition thickness can depend on the thickness of the thermal barrier coating (TBC) and the shape of the cooling holes. In Zagnoli et al.\cite{13} a two plate setup was used to study impingement cooling and the effect of a pin array on deposition. Zagnoli et al. demonstrated that the capture efficiency (CE, Eq 1) depended on the metal temperature and pressure ratio. Peterson\cite{14} and Whitaker et al.\cite{15} used a cylinder with an insert to represent the leading edge of a turbine blade. These studies found that changes in the particle loading had little effect on the internal blockage due to deposition. Additionally it was shown that blockage occurs due to a buildup of the smaller particles (>5 \(\mu\)m) and that it can be eroded by larger particles.
\[
CE = \frac{\Delta m_{\text{testplate}}}{m_{\text{Injected}}} \quad (1)
\]

Cardwell et al.\cite{16} studied clogging in different geometries of film cooling in a double walled liner, and found that blockage increases with temperature and alignment of the impingement and film cooling holes. They suggest that a high overlap between the impingement and film cooling holes results in a higher blockage. While work with double walled cooling, which is common in turbine blades, is very common, less work has been done looking at the effects of deposition in single walled film cooling flow, which is commonly found in the combustor section of an engine. Walsh et al.\cite{17} looked at sand-blocking in single wall film cooling holes, finding that, at engine-representative temperatures, blockage decreases as the pressure ratio is increased.

Because of costs and difficulties of testing at engine-relevant conditions, computational fluid dynamics (CFD) is often used to test the effects of different variables on flow through an engine. Modeling flows can prove difficult due in part to complex geometry, upstream influence, and mesh size requirements. Ideally a whole engine could be modeled; however this is essentially impossible with current solution methods. Zagnoli\cite{18} modeled a full rotor stator stage with both steady and unsteady calculations and then tracked particles through the converged solutions. Many CFD studies have been done on flow through an effusion cooling hole including Repko et al.\cite{19}, Kampe et
The effects of partial blockage of cooling holes were investigated numerically by Cheng-Xiong et al.\textsuperscript{[22]}. Once particles are tracked through a converged steady state flow solution, the deposition must be modeled. The simplest method is to assume that any particle reaching the surface will deposit as areas with lots of impacts tend to see more deposition. A critical velocity model was used by El-Batsh\textsuperscript{[23]} which biases sticking to low velocity impacts of small particles only. Casaday\textsuperscript{[2]} compared several sticking models to experimental results and found that one based on wall shear with geometry adaptation was the most accurate, and reproduced trends based on temperature and Reynolds number seen in the experimental data. The critical viscosity deposition model of Tafti and Sreedharan\textsuperscript{[24]} was used by Zagnoli et al.\textsuperscript{[13]} and compared to experimental results.

This study focuses on the deposition occurring in effusion cooling holes representative of those found in a combustor liner. Of specific interest is the effect of the direction of flow as it approaches the cooling hole and how it changes the structures that form and the resulting flow restriction. Additionally the experimental results are used as a point of comparison for a computational model.
Chapter 2: Experimental Setup

Testing for this study was performed in the Aerospace Research Center (ARC) at The Ohio State University. This study looks at the effect of turning angle on the deposition in a single wall cooling hole at temperatures representative of a combustor liner in a gas turbine.

Test Hardware

For the experimental section test coupons were designed with effusion holes to mimic the cooling holes in a section of combustor liner. The impingement plates (Figure 2) are 50 mm x 127 mm x 1.27 mm and made out of a nickel alloy. The testing area of each coupon measures 25.4 mm x 101.6 mm and has 163 effusion holes with a nominal diameter of 0.45 mm (0.018 in).
These effusion holes are arranged in staggered rows of 12 and 13 holes, spaced 1.9 mm (0.075 in) apart. Each row the holes are spaced 7.62 mm (0.3 in) apart. Figure 3 shows a drawing of the layout of holes on a test plate. The holes are all angled at 70° off of normal.

![Figure 3: Hole Layout Drawing (dimensions in mm)](image)

Test Facility

A diagram of the experimental facility designed for this study is shown in Figure 4. The test coupons are attached to a hastelloy plenum mounted through the wall of a kiln. The kiln is used to maintain a constant back side coupon temperature during a test. The target surface temperature of $T_{\text{plate}}=870^\circ\text{C}$ is representative of actual conditions surface of a combustor liner. This temperature can be monitored through a sapphire window in the kiln using an infrared (IR) camera. Cooling air is controlled with a 0-
100 SLPM massflow controller with an uncertainty of 0.8% reading + 0.2% full scale. For the typical massflow of 46 slpm, this amounts to an uncertainty of ±0.57 slpm or ±1.24%. Outside of the kiln, dust is injected into the cooling air, which is preheated with heat tape, after which the air travels through an equilibration tube (length = 0.635 m), to allow the dust to reach the flow temperature, and into the plenum. The preheating of the air allows for the independent variation of both the cooling air and back side temperature of the test coupon if desired. Thermocouples are used to monitor the temperature of the kiln, coolant in the plenum, and the air temperature at the dust injection point during each test. Each thermocouple has an uncertainty of the greater of ±2.2°C or ±0.75% reading. A 2.5 psi differential pressure transducer, accurate to ±0.08% full scale, is used to measure the static pressure of the air in the plenum 1.3 cm upstream of the test coupon compared to the ambient pressure outside of the kiln. Because the kiln is not airtight it is assumed that the pressure in the kiln is the same as ambient. Since Back Flow Margin (BFM) was held approximately constant at 3% for all the tests, the uncertainty in this measurement ranges from 2.95 to 3.05%. The entire rig is controlled and monitored using a custom LabVIEW VI interface.
Figure 4: Experimental Facility Setup
A simple particle tracking simulation was done to estimate the length of equilibration tube needed for different particle sizes of ARD to equilibrate with the surrounding flow. Figure 5 shows that particles with a diameter of 10μm reach the flow temperature within 10mm.

![Figure 5: Particle Equilibration Analysis [14]](image)

The differential pressure across the test plate is used to find the backflow margin (BFM, Eq. 2) of the plenum which is held constant for all tests. Since as the BFM is matched then the pressure ratio and Mach number are also matched. When the flow temperature is also matched then exit velocity is matched. Finally by matching absolute pressure, which is done by using ambient as a reference point, density is constant so it is known that the Reynolds number is constant between tests.
\[ BFM = \frac{P_{\text{Plenum}} - P_{\text{Ambient}}}{P_{\text{Ambient}}} \times 100 \]

For these tests the BFM is held constant at 3% using a mass flow controller and simple proportional controller to adjust the set point. The dust is injected into the cooling air using a pressurized conveyor belt and funnel system. This allows for accurate and steady injection of small amounts of dust over an extended test time. The feed rate is controlled by a stepper motor attached to a speed reducer.

**Plenum**

The plenum (Figure 6) used in this study was designed so that it stalls consistently in order to control the flow direction impinging on the effusion holes. This means the flow will always impinge on the same side of the test coupon and then flow to the other regardless of the coupon orientation. Modifying the direction the coupon is mounted results in the impinging flow either being turned favorably or adversely as depicted in Figure 7. To better understand exactly how the flow stalled, the front of the plenum was replaced with a clear replica and the flow was interrogated using Particle Image Velocity (PIV).
Figure 6: Plenum

Figure 7: Sample Plenum Velocity Distribution, Mean Favorable Turning Angle 10°, Mean Adverse Turning Angle 130°
Setup and experimental procedure

The front rectangular section where instrumentation is normally mounted was replaced with a clear acrylic replica and the flow was captured in 2D using a single camera LaVision PIV suite with a Nd:YAG laser. Because of the high aspect ratio of the test area (101.6 mm x 25.4 mm) it was assumed there is little to no out of plane motion in the core flow where the PIV was taken, and that the flow is steady. The laser sheet was brought in through a short side and the camera was mounted above (Figure 8). Due to the material limitations of the acrylic, the PIV study was conducted at $T_{\text{ambient}} = 20^\circ\text{C}$ (vs. $540^\circ\text{C}$ for the deposition experiments). Air was seeded with olive oil particles having diameters between 1 and 2 $\mu\text{m}$ and expanded in the plenum as it would during a test. Lastly, the end of the rig opposite the laser sheet was fitted with a pressure tap (Figure 8). The pressure tap allowed the BFM to be calculated and used to match inlet conditions in the CFD simulations.
Because experimental tests are run with a flow temperature of 540°C the change in density had a major effect on the flow between the PIV and deposition cases. This meant that there was no way to match both the mass flow and flow velocity of a deposition case when collecting PIV. The mass flow required to match exit velocities was estimated using the method shown in Eq 3 along with using experimental data. This
mass flow was found to correspond to a BFM of 7.7% in the acrylic extender at room temperature conditions. PIV data was collected at a number of different BFMs between 3% and 8.8%. The low end (3%) matched the experimental pressure drop, while the high end (8.8%) was used to gain a better insight into how the stall is affected by the flow velocity in the plenum. This was done with a plate mounted in both a favorable and adverse directions. Having the data from a range of BFMs meant that with the CFD either mass flow or exit velocity could be matched.

\[
V_c = V_h \Rightarrow \frac{\dot{m}_c}{\rho_c A} = \frac{\dot{m}_h}{\rho_h A} \Rightarrow \dot{m}_c = \dot{m}_h \frac{\rho_c}{\rho_h}
\]  

\( (3) \)

**Velocity Measurements**

The velocity data for each flow were calculated using the DaVis software from 200 image pairs using a multi-pass algorithm. The final pass had a 32x32 pixel window with a 75% overlap between windows. Figure 9 shows a sample the solution. The 3

![Sample Flow Solution in the Plenum](image_url)
thick black vertical lines mask regions of the flow that were blocked by screws. Looking at Figure 10, which compares the incoming flow angle for three different flow speeds at \( y = 36 \text{ mm} \), it is clear that the shape of the flow and stall are independent of flow speed.

Figure 10: Comparison of incoming flow angle at different flow speeds at \( y = 36 \text{ mm} \).

Once the flow angles independence from BFM was established with a test plate mounted in a favorable configuration, the plate was reversed so that its effects on the flow could be investigated. Again changing the BFM only had an effect on the flow rate not the flow angle. Figure 11 shows a side by side comparison of the different plate
directions. A comparison of the incoming flow angle slightly above the test plate (at $y = 36$ mm) is shown in Figure 12. When compared this way it is evident that there are little to no upstream effects from the plate orientation.

Figure 11: Velocity magnitude Contours for Different Plate Directions
Figure 12: Comparison of Incoming Flow Angle with Different Plate Directions at $y = 36$ mm

By looking at the velocity components of the flow as close to the effusion holes as the PIV could resolve an estimate for the flow turning angle can be calculated using simple trigonometry (Eq. 4) where the plate and flow angles are measured from the x-axis in the counterclockwise direction (Figure 13). It was found that the turning angle of the flow did not depend on the BFM or mean flow velocity. For the favorable case the turning angle ranges from $80^\circ$ to $0^\circ$ along the plate in the positive x direction with an area-weighted mean of $10^\circ$. In the adverse configuration the turning angles range from $65^\circ$ to $150^\circ$ and an area-weighted mean of $130^\circ$. 
\[ \theta_{flow} = \cos^{-1}\left(\frac{U_x}{U}\right) \]

\[ \theta_{plate} = \begin{cases} 
20 & \text{Favorable} \\
160 & \text{Adverse} 
\end{cases} \]

\[ \theta_{turning} = \text{abs}(\theta_{flow} - \theta_{plate}) \]

Figure 13: Turning Angle Diagram

*Heating*

It is common to use combustion as a heat source in high temperature deposition studies. Zagnoli *et al.*[^13] used a propane combustor, and Prenter *et al.*[^10] used a natural...
gas combustor as a heat source. In both of these cases the combustion exhaust itself is used as the hot air flow. This means that the test section is subject to combustion byproducts. As long as the flame is kept lean there is usually no problem, however rich combustion can result in soot depositing on the test section and ruining a test. One last issue with combustion is temperature variations due to unsteadiness in the fuel and air supplies.

To avoid any issues with combustion this test rig was built using only electrical heating systems. The plenum and backside of the test coupon are heated using an electric kiln. The kiln allows for constant and uniform heating of the test coupon to temperatures representative of a combustor liner. The kiln set point used was 980 °C. The air entering the plenum is preheated using two independently controlled heat tapes wrapped around the outside of the pipes

*Feed System*

Several methods were considered for injecting dust, the plunger method was discarded due to the need of short tests to maintain an even feed rate. A hopper-with-auger method was also discarded due to the volume of dust needed to make it efficient. Eventually a modified version of the sealed conveyor belt used in Peterson\textsuperscript{[14]} was built due to its ability to inject a small amount of dust with a constant rate over an extended time period.
The system, shown in Figure 14, consists of a motor, a 60:1 speed reducer and a 216 mm conveyor belt. All the components are housed in a sealed polycarbonate enclosure fitted with a clear lid. Sealing the enclosure was made easier by moving the motor and speed reducer inside and removing the need to seal around a rotating shaft. Like the original design a brush mounted under the front roller dislodges any dust stuck to the belt and feeds it into the funnel. This set up can deliver between 0 to 6 grams of dust over times from less than a minute to 7.5 hours. Because the enclosure is polycarbonate, static electricity control is important during test setup and operation as it
has been observed that dust on the feed belt can jump over 2 inches to stick to the lid. This was prevented by carefully washing and drying the lid before every test.

*Particle Selection*

The dust used in the experimental tests is 0-10 μm Arizona Road Dust (ARD), a test dust commonly used in deposition studies such as Cardwell et al.\textsuperscript{[25]} and Casaday\textsuperscript{[2]}. The manufacturer’s size distribution is shown in Figure 15. This size range is consistent with Dunn’s\textsuperscript{[1]} findings that the mean particle diameter of dust exiting the compressor of an engine was 6 μm. Also, Whitaker et al.\textsuperscript{[15]} showed that most deposition occurs with particles smaller than 5 μm and can be eroded by anything larger.

![Figure 15: Size distribution of 0-10 μm Arizona Road Dust (Powder Technology Incorporated\textsuperscript{[26]})](image)

ARD is a standard test dust used to represent dust ingested from flight over desert or dusty environments or through volcanic ash. The relevant composition of ARD was recorded by the manufacturer. Heiken\textsuperscript{[27]} compiled the relative chemical composition
over several different volcanic events, and Gislason et al.\textsuperscript{[28]} recorded the composition of the 2010 eruption of Eyjafjalajökull, all of their findings are compiled in Table 1.

<table>
<thead>
<tr>
<th>Ash Type</th>
<th>Density $\rho$ (kg/m$^3$)</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona Road Dust</td>
<td>2650</td>
<td>72.00</td>
<td>12.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.00</td>
<td>1.50</td>
</tr>
<tr>
<td>Magmatic Basaltic</td>
<td>-</td>
<td>49.57</td>
<td>15.79</td>
<td>11.41</td>
<td>10.29</td>
<td>2.69</td>
<td>7.43</td>
</tr>
<tr>
<td>Magmatic Andesitic/Rhyolitic</td>
<td>-</td>
<td>63.40</td>
<td>16.20</td>
<td>4.95</td>
<td>4.74</td>
<td>4.14</td>
<td>1.95</td>
</tr>
<tr>
<td>Magmatic Carbonatite</td>
<td>-</td>
<td>25.23</td>
<td>5.27</td>
<td>8.71</td>
<td>14.10</td>
<td>18.65</td>
<td>1.62</td>
</tr>
<tr>
<td>Hydrovolcanic Basaltic</td>
<td>-</td>
<td>46.18</td>
<td>14.53</td>
<td>10.94</td>
<td>9.68</td>
<td>3.71</td>
<td>7.02</td>
</tr>
<tr>
<td>Hydrovolcanic Rhyolitic</td>
<td>-</td>
<td>75.40</td>
<td>13.50</td>
<td>0.92</td>
<td>0.42</td>
<td>3.80</td>
<td>0.10</td>
</tr>
<tr>
<td>Eyjafjalajökull, 2010</td>
<td>-</td>
<td>57.98</td>
<td>14.87</td>
<td>9.75</td>
<td>5.50</td>
<td>5.01</td>
<td>2.30</td>
</tr>
</tbody>
</table>

When only comparing compositions, ARD seems to be a relatively good representation of volcanic ash, even though there is a higher concentration of SiO$_2$ in ARD than any of the reported ashes. However when ARD and ash from Eyjafjalajökull were compared by Kueppers et al.\textsuperscript{[29]} it was found that the melting point of the volcanic ash was substantially lower due the different phase states of the SiO$_2$ and other constituent parts. ARD is still used as the test dust in this study as it is readily available, so results are easily comparable to other papers.

**IR Camera**

The required kiln setting to achieve the desired backside temperature on the test coupons was found by monitoring the test section with a Cedip Silver Infrared Camera.
with a 5 μs integration time through a sapphire window mounted in the kiln. A sample image is shown in Figure 16. In the IR images it is possible to not only see the cooled section of the test plate but also the individual cooling holes.

![Example IR Image in Digital Level](image)

**Figure 16: Example IR Image in Digital Level**

Since the IR camera outputs a digital level, a calibration was performed by welding a thermocouple to the outside face of a test coupon. The thermocouple was attached to the outer edge of the coupon, as shown in the lower left corner in Figure 16, so that it did not affect the effusion holes. Because of its location the thermocouple did not give an accurate reading of the test section temperature and could not be used in place of the IR camera. During warmup of the kiln the temperature was held at values between 760°C and 1000°C and the system was allowed to soak for 15 minutes without coolant flow. After the plate reached steady state an IR image was captured and the temperature of the attached thermocouple was recorded. The digital level around the thermocouple
was plotted against the known thermocouple temperature and fitted with a power law curve (Figure 17). The fit found for the curve is given in Eq 5.

\[ T = 12.161(DL)^{0.5011} \quad (C) \]  

Figure 17: IR Calibration Curve

The calibration gives a good estimate of a test coupon’s temperature at the start of a test. However the dust deposits on the outside out the plate have a different emissivity and prevent the overall plate temperature from being known once a test has started. Because of this the kiln temperature is held constant during a test at a single set point that was chosen from initial tests to give a relatively steady coupon temperature of 870°C.

Due to technical difficulties, IR was only captured on a third of tests, however the images
captured and the initial testing showed that this method results in a consistent and repeatable plate temperature between tests.

Temperature Correction

Because a kiln is used to supply heat (980 °C) to the back side of a test coupon there is a large amount of radiative heat transfer in and around the plenum. The plenum is insulated to prevent the kiln having too large of an effect on the flow during a test. However the metal is commonly over 860°C and can get up to 930°C. With the metal temperature so high the flow thermocouple in the plenum is essentially being heated by radiation from the wall and then cooled by the flow over it. This results in false readings higher than the actual flow temperature, sometimes by as much as 190°C. The installation of a radiation shield between thermocouple and the plenum wall did not fix this problem. Instead this error is corrected by using a twostep iterative energy balance. In the first step the flow temperature is calculated using the method laid out in West and Westwater\textsuperscript{[30]} where conduction, convection, and radiation are all taken into account. Since the flow thermocouple is an exposed bead the Nusselt number is estimated as flow around a sphere. A schematic of where temperatures are measured in the plenum is shown in Figure 18. After the flow temperature is calculated another energy balance is used to estimate the inner wall temperature of the plenum (Eq. 6). The emissivity of the plenum was estimated as 0.85 for hastelloy. This value was taken from Omega\textsuperscript{[31]}. The complete code is given in Appendix A.
Heat Flux Through wall = Heat Flux to Flow

\[
\frac{k}{l}(T_{wi} - T_{wo}) = h_w(T_f - T_{wi})
\]  

(6)

\[
T_{wi} = \frac{k_w T_{wo} + h_w T_f}{h_w + \frac{k_w}{l}}
\]

The iteration is considered converged when the flow temperature doesn’t change more than 1 K between iterations, this normally happens within 20 iterations. The flow temperatures in the plenum reported in this study are all corrected using the method described. All other reported experimental temperatures are the direct thermocouple reading.

Test Procedure

The coupon is weighed and mounted to the plenum using twelve 4-40 bolts with a 1/8 inch millboard gasket. In order to prevent leaks and aid in disassembly the bolts are
coated in a lead anti-seize. Once the coupon is attached the kiln and plenum surface temperature thermocouples are put in place, and the plenum is wrapped in insulation before closing the kiln. Lastly the dust is weighed and spread out on the conveyor belt. This is done using specially designed walls and a scraper to lay the particulate out in a repeatable and even manner along the belt. The dust is weighed to within ±0.005g, and all the weighed dust is assumed to be injected. While this is not the case, dust can be seen stuck to the weighing cup and conveyor belt for example, these losses are of the order of 0.015g and present in all tests.

Once everything is assembled an initial flow check is performed to ensure that there are no leaks and everything is working properly. This flow check is also compared with a similar check done after the main test has cooled back down to ambient. To minimize any blockage lost due to shear in a post flow check these flow checks don’t go up to the test BFM of 3.0%. The flow checks consist of recording data at BFMs of 0.0%, 0.5%, 1.0%, 1.5%, and 2.0%. Figure 19 shows a selection of pretest flow checks from both favorable and adverse tests comparing the mass flow needed to maintain various BFMs, two for each condition. There is a very slight increase in mass flow between the plate orientations. This is of the same order (0.0001 kg/s ≈ 5 slpm) as the difference in mass flow due to plate defects for plates in the same orientation.
After the flow check is completed the kiln is turned on and allowed to heat up. During this time a flow of about 40 SLPM is maintained through the system to keep upstream components cooled. As the kiln set point is approached the flow is changed to maintain the desired test BFM of 3.0% and the heat tape is turned on. After the kiln has reached its set point the test rig is allowed to sit to ensure that it is at thermal equilibrium. While the rig is resting a pre-test data file is recorded so that the conditions before any test can be recalled is necessary.

Once all the test conditions are met the test is started. During a test the heat tape set point is manually adjusted in an attempt to maintain the flow temperature. However
as the flow rate decreases the heat absorbed through the plenum rises and there is an increase in flow temperature. Most tests see a rise of 65°C over an hour long test. Because this temperature rise is dependent on blockage the adverse tests tend to have a higher mean test temperature by about 10°C. If IR is being recorded during a test a single frame is captured every 5 minutes. Due to the length of the test this is all that is required to get a solid understanding of how the plate temperature is affected by deposition over the course of a test.

After finishing a test all the heating elements and flow are turned off and the test rig is allowed to cool. Initial cooling is augmented with a small trickle flow which also stops upstream temperatures from increasing. Once everything has cooled back to room temperature a second flow check is performed to mirror the one taken before the test. Lastly the test coupon is removed, this is done by breaking the bolts, and the final weight is measured. The test coupons are weighed on a scale accurate to ±0.00005g.

Post Test Procedure

Several analysis techniques were used on different test plates in order to study the deposition on and in the coupons including scanning the outer surfaces. The main methods used were sectioning the plates to look at deposition in the holes, and shining light through a test section. Scanning the coupon is done with a NextEngine 3-D laser scan system to characterize the deposition of dust on the inside surface in a method similar to Zagnoli et al.\textsuperscript{[13]}. To achieve this characterization the coupon is firmly clamped to the scanning fixture (Figure 20) so that the plate remains in the same position in the scanner's field of view and the two cannot move relative to each other. The deposits on
the plate are then scanned and saved. Without moving the test plate, the surface is then brushed clean and scanned a second time. These two scans are subtracted from each other, leaving just the deposited sand heights. This method allows for the creation of contour graphs showing deposition heights and locations for easy comparison between tests. The laser scanner has an accuracy of ±60 μm.

Figure 20: Scanner Setup

It was found that the resolution on the size of the laser scanner was not good enough to resolve the details of the back side deposition. Because of this a Veeco Contour GT-K optical profilometer (OP)\textsuperscript{32} was used to look at a small area in more
detail. The profilometer has a 1 mm X 1 mm window which can be stitched together while scanning. By stitching together 24 windows with a 5% overlap an area covering two effusion holes was scanned. This scanner is accurate on the nanometer scale. Because of the limited depth of scan the OP could take, the scans could not look inside an effusion hole. After scanning each plate section the data was post-processed, coarsened to aid in computation time, and plotted using both the OP’s operating software and custom MatLab scripts. Unlike the laser scanner the OP requires only a single pass which does not disturb the deposit on the test plate.

To study the buildup of dust inside the effusion holes some coupons were potted in epoxy instead of being scanned. The epoxy used was Struers EpoFix epoxy. This epoxy was chosen because of its relatively low viscosity for a two part epoxy, making it easier to fill the small effusion holes. After a test plate is removed from the kiln it is suspended in an acrylic mold which is then carefully filled with epoxy and allowed to cure fully. The coupon is then removed from the mold and sectioned. Initial sectioning is done on a bandsaw after which the plates are milled until a row of effusion holes is reached. Tooling marks are removed from the plates by polishing with increasingly fine grades of sandpaper, from 400-1000 grit. Finally the exposed holes are photographed under magnification with a USB microscope. A test plate can normally be sectioned twice revealing between 24 and 26 effusion holes.
Figure 21: Light Test Fixture

One final method that was used to qualitatively see which holes were blocked was to mount the plate over an LED. The fixture shown in Figure 21 was designed to hold a plate so that an LED array mounted on the bottom shines directly through the effusion holes. When this is done in a dark room it is immediately obvious if a hole is blocked or not. Additionally holes with a flow restriction can be seen by comparing relative intensity of light in a hole to that of a plate with no deposition. Because this test does not disturb any deposition a coupon can also be potted or sectioned afterward.
In addition to the experimental test with a flat plate a companion CFD study was conducted. The study focused on a small subsection of the test coupon and investigated the accuracy of estimating deposition with first-impacts as well as using the deposition model presented in Bons et al. The CFD model boundary conditions were matched to experimental conditions. Due to time and computational limits the test coupon was assumed be a uniform temperature (871 °C). While this is not ideal the thin plate and high thermal conductivity of the test plate make it a good first order approximation. The inlet flow temperature was also held constant across the inlet at 540 °C.

Grid

It would be ideal to perform a CFD simulation of the entire plenum and effusion plate due to the change in flow speed and direction impinging across the plate evident in the PIV. That however would require a very large mesh and be computationally prohibitive. Instead, the smallest periodic section of a test plate was identified. A total of one effusion hole modeled by using the periodic and symmetry boundary condition, shown in Figure 22. The resulting unstructured mesh had 819,021 cells and was generated in Pointwise from a CAD model of a plate section. The plate was not included in the computational mesh. The inlet plane is 10 hole diameters above the test plate.
Another aid to reduce the computation time was to assume that the incoming flow is constant along the inlet plane. It was shown in the PIV (Figure 10 and Figure 12) that the turning angle of the 2D flow changes along the length of the test plate. To account for this, four CFD solutions were converged using different inlet velocities based on the PIV data from a single flow condition in the actual plenum. Three of these inlet conditions were calculated by averaging small sections of the PIV data, about the length (7.62 mm) of the computational grid, parallel to the plate at a distance equal to the inlet
The plane of the model (≈ 4.5 mm from the surface or y=36 mm). These three locations were chosen to be low, medium, and high inlet speed. The fourth flow speed inlet condition is an average of the entire plane. Figure 23 shows the approximate areas used to calculate the averaged inlet velocity for the first 3 cases.

![Figure 23: Areas of Averaged flow for CFD inlet conditions, 1) Low Speed, 2) Medium Speed, 3) High speed](image)

**Flow Solution**

The flow was converged using 3D numerical simulations of the Reynolds-averaged Navier–Stokes equations (RANS) performed using the commercial finite volume code, FLUENT™. The flow solution included conservation of mass, momentum, and energy for compressible, turbulent flow. The turbulence was modeled using the k-ω-SST model with an inlet turbulence of 5%. The k-ω-SST was used to match previous work with flow in effusion holes, which used both k-ω [19][21] and SST [20] models. The boundary conditions required for the solver are velocity, total
temperature, turbulence intensity, and turbulence length scale at the inlet, with static pressure specified at the outlet. These boundary conditions are set to mimic the experimental facility as closely as possible and can be found in Table 2. An initial solution was converged 5000 iterations; other cases started with this solution as the initial guess and were converged over another 5000 iterations. The PIV data collected at BFM of 4.1% and 7.7% were used to generate the inlet conditions, with 4 flow speeds for each BFM and plate orientation this results in sixteen individual cases. Of the sixteen individual cases, three developed oscillations in the residuals and failed to converge due to their flow speeds being too high.

Table 2: CFD Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>811 K</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>1145 K</td>
</tr>
<tr>
<td>Inlet Turbulence</td>
<td>5%</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>101325 Pa</td>
</tr>
<tr>
<td>$V_y$</td>
<td>0.78 - 1.6 m/s</td>
</tr>
<tr>
<td>$V_x$</td>
<td>0.3 - 4.0 m/s</td>
</tr>
</tbody>
</table>

**Validation**

The flow solutions, samples of which are shown in Figure 24, were validated by comparison to deposition experiment and PIV data. Both the PIV and CFD solutions show the upstream effect of the effusion holes to be negligible with only significant influences appearing in the flow close to the effusion holes, about 5 hole diameters ($\approx$2.54 mm).
The flow solution was also compared to data for the deposition experiments, such as mass flow rate, BFM, and exit velocity. The experimental effusion hole exit velocity was estimated using the measured mass flow, flow temperature and hole diameter, while the CFD exit velocity was calculated as the mass weighted average of the flow exiting the holes. Experimental values and some CFD values are shown in Table 3. It is immediately obvious that inlet velocities derived from the 7.7% BFM PIV result in much more flow than the experimental case, while the 4.1% BFM more closely match both mass flow per hole and estimated exit velocity. Also no case matches BFM very closely. Even though the PIV was taken at ambient conditions so only mass flow or exit velocity could be matched the CFD takes into account the change in density so with the right inlet
conditions both can be matched. The higher flow speeds at lower massflow seen in the CFD are most likely due to differences in temperature, and so density between the computational and experimental cases, and the possibility for manufacturing defects in the test plates. Since Fluent was given inlet velocity conditions, it will use whatever driving pressure is required to achieve those speeds and so won’t match BFM. Because the inlet velocities are averaged from the PIV values the BFM would be extremely hard to match without modeling a complete row of effusion holes and varying the inlet velocity across it. As such it was determined to focus on the 8 CFD cases calculated from the 4.1 % BFM as they more closely match the experimental results. The other cases were treated as a higher flow condition.

<table>
<thead>
<tr>
<th>Table 3: Comparison of CFD and experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
</tr>
<tr>
<td>BFM</td>
</tr>
<tr>
<td>Mass Flow (kg/s)</td>
</tr>
<tr>
<td>Exit Velocity (m/s)</td>
</tr>
</tbody>
</table>

The flow entering the effusion hole shows the same shape as seen by Leylek and Zerkle\cite{34} as well as [19]-[21]. A side by side comparison of this flow solution with Leylek and Zerkle can be seen in Figure 25.
Figure 25: Flow Solution compared to Leylek and Zerkle\textsuperscript{[34]}

\textit{Grid Independence}

To ensure the accuracy of the flow solution a grid independence study was conducted using a grid refined in Pointwise. Two cases, one favorable and one adverse were compared. The refined grid was created by increasing the number of nodes in all directions by a factor of 1.27. This resulted in slightly less than double the number of
cells (819,000 to 1,438,330 cells). The two solutions were converged independently of the original solutions. After converging the solution on each of the refined grids the mass flow and mean hole exit velocity for each case were compared to the original solution. The difference between the refined and unrefined case were on the order of 7%. This was not as small as desired (>3%) but was considered acceptable.

Particle Injection

Particle tracking was done with FLUENT’s built in Eulerian-Lagrangian model, or Discrete Phase Model (DPM). In a steady state calculation the DPM is used after the flow solution has fully converged. Trajectories of particles are calculated by stepping forward in time and balancing the flow induced forces on the particle with the particle's inertia at each step. Work done by Elghobashi[35] classified interactions between particles in flow. In the one way coupling regime the particle has no effect on the flow of other particles. Because of the low experimental loading, on the order of 0.1 grams of dust per cubic meter of air the test is within the one way coupling regime. In the CFD solution this one way coupling allows a large amount of particles to be tracked together. This trajectory is stored for each particle.

When tracking particles using this method, drag is the dominant force [2][36]. Because of this other forces such as thermophoretic forces and Saffman lift were neglected. Because of the small diameter of the simulated particles, 1-10 μm, the Reynolds number is small; the flow around the particles is in the Stokes flow regime. When the hole diameter is used as the characteristic length, for a 10 μm particle the stokes number is of the order 3e-5. Particle diffusion due to turbulent eddies was modeled.
with a random walk method. This turbulent diffusion works by randomly modifying the flow direction and intensity seen by a particle, using the turbulence values calculated in the k-ω-SST solution. Turbulent diffusion means that each particle injected has a unique trajectory even when initialized with the same conditions.

These simulated particles were initialized with the same incoming flow speed and temperature as the fluid in each case. The particles injected were chosen to mimic the 0-10 μm ARD used in the experimental cases. The particles had diameters of 1, 2, 4, 6, 8, and 10μm, and a density of $\rho=2650$ kg/m$^3$. In each injection approximately 96000 particles, evenly distributed between sizes, were simulated.

_Deposition and Impacts_

<table>
<thead>
<tr>
<th>ARD</th>
<th>Density [26]</th>
<th>2650 kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young’s Modulus [33]</td>
<td>$104e9$ Pa</td>
</tr>
<tr>
<td></td>
<td>Yield Strength [33]</td>
<td>$130e6$ Pa</td>
</tr>
</tbody>
</table>

When FLUENT detects that a particle impacts a surface a user defined subroutine was used to determine if the particle deposited. If the particle was not determined to deposit its CoR was calculated. This means that one particle could impact the test plate several times before depositing or escaping the simulation. The function used to determine deposition and rebounds is laid out in Bons et al.$^{[33]}$. This explicit model treats particles as cylinders impacting end on, and takes into account physical effects such as deformation, both elastic and plastic, adhesion forces and removal due to shear.
Additionally the effects of temperature on material properties are taken into account. The explicit nature of this method drives computational times down by removing the need to iterate a solution for each particle as some other models do. The material properties used for the impact model and tracking the particles are given in Table 4. These values were held constant for all cases, with no adjustment for temperature.
Experimental Results

All deposition experiments were run under identical test conditions (Table 5) varying only the coupon direction. During each test the deposition on a test plate is evident through the reduction of mass flow needed to maintain the target BFM due to the reduction of flow area. This is the main way of monitoring the dust build up during a test and estimating total blockage.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BFM</td>
<td>3%</td>
</tr>
<tr>
<td>Plate Temperature</td>
<td>870 °C</td>
</tr>
<tr>
<td>Coolant Temperature</td>
<td>540 °C</td>
</tr>
<tr>
<td>0-10 ARD</td>
<td>0.65 g</td>
</tr>
<tr>
<td>Target Time</td>
<td>60 min</td>
</tr>
</tbody>
</table>

*Favorable vs. Adverse (Directional Tests)*

In the favorable configuration tests, the average reduction in mass flow over the course of a run was 27% while the adverse plates had a much higher mass flow reduction of 62%. The time history of flow during a test is shown in Figure 26, where the time has been normalized by the length of each test, and the reduction is mass flow is normalized
by the starting mass flow. Both cases show a fairly linear reduction in mass flow over the whole test, the direction of the impinging flow has a large effect on the slope of this reduction and so the rate of clogging in the film cooling holes. This reduction in flow for both test cases is significantly different from that seen by Walsh et al. who saw reductions on the order of 10% with a comparable amount of dust, this may be due to slightly different operating conditions or the different test geometry, Walsh et al. used a circular annulus instead of a flat plate.

![Figure 26: Example time history of mass flow reduction for both plate configurations](image)
By comparing the mass flow required to achieve different BFMs at ambient conditions the flow checks performed before and after each test give another way to assess flow blockage. This method of looking at blockage tends to give slightly lower values of blockage than looking at the flow change over a test. It is suspected that this is because some deposits might become loose during cooling and then dislodge when air is passed through the holes. Two flow checks are compared in Figure 27 and the mean percent reduction in mass flow for various BFMs is given in Table 6. These flow checks again show a large difference between the blockages caused by the turning angle of the flow.

![Figure 27: Comparison of Post Flow Check for Different Turning Angles](image)

Figure 27: Comparison of Post Flow Check for Different Turning Angles
Table 6: Mean Flow Check Percent Mass Flow Reduction from Post Test (0.5 – 2% BFM) and end of Deposition (3% BFM)

<table>
<thead>
<tr>
<th>BFM</th>
<th>0.5%</th>
<th>1.0%</th>
<th>1.5%</th>
<th>2.0%</th>
<th>3.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favorable</td>
<td>24.42%</td>
<td>27.31%</td>
<td>22.26%</td>
<td>20.80%</td>
<td>27%</td>
</tr>
<tr>
<td>Adverse</td>
<td>60.32%</td>
<td>58.65%</td>
<td>58.08%</td>
<td>57.34%</td>
<td>62%</td>
</tr>
</tbody>
</table>

After the test section is removed the impingement side is imaged. Figure 28 shows the complete test plate from a favorable and an adverse test. Because of the light color of ARD it is relatively easy to see the dust patterns left due to its high contrast with the dark metal of the oxidized test plate. The first feature that is immediately apparent is the large amount of dust deposited on the left side of the plate in both directions. This large build up is to be expected as the PIV shows this is where the flow impinges (Figure 12) and so this area will have more impacts and significantly increased deposition.

Figure 28: Complete Test are post Test, A) Favorable b) Adverse
When light is shone through the test sections it is clear when holes are blocked completely, it can also be seen when the flow area is reduced. Figure 29 shows a favorable and adverse test plate, in the same orientation as Figure 28, as well as a clean test plate for comparison. It is imminently obvious that a large swath of holes are blocked in the adverse case, while only some of the effusion holes around the edge of the favorable plate are completely blocked. Additionally in both test cases the unblocked holes don’t appear as perfectly oval or as bright as the holes in a reference test plate suggesting a reduction in flow area that does not completely clog these holes. By processing these images within MatLab it is possible to count the holes and get a mean intensity of the light in the holes. These values are shown in Table 7. It should be noted
that the LED fixture blocks a row of holes leaving only 156 of the 163 holes visible. While almost all the holes are visible for the favorable plate there is a clear drop in the overall intensity. This suggests a small number of completely blocked holes and a restriction in almost all the other effusion holes. The adverse case shows both a large number of blocked holes and heavy restriction in the unblocked holes. These reductions are comparable to those shown in Table 6 from the end of test and post-test flowchecks.

<table>
<thead>
<tr>
<th></th>
<th>Visible holes</th>
<th>Mean Intensity (on a 0-255 scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favorable</td>
<td>146</td>
<td>141.5</td>
</tr>
<tr>
<td>Control</td>
<td>156</td>
<td>164.6</td>
</tr>
<tr>
<td>Adverse</td>
<td>65</td>
<td>89.0</td>
</tr>
</tbody>
</table>

Some test plates were sectioned to investigate how ARD was depositing in the effusion holes. A selection of these images is shown in Figure 30. The three main parts of the image are the plate (silver), the dust (red-brown), and the epoxy (white or clear). The first row of images is of clogged holes in each plate orientation, and the second row shows holes that are not yet fully blocked. In both cases the dust deposited in the effusion holes looks fairly similar. This would suggest that the flow inside of the effusion holes is similar between the two cases as seen in the CFD solutions (Figure 24).
Repeatability

Since not all the test plates undergo the same posttest processing the primary measures of repeatability in a test are the conditions recorded during a test and posttest images. A total of twelve tests were run with six in each plate orientation. The repeatability of the test conditions is given in Table 8. It should be noted that the initial favorable test was run over only half an hour while all other tests were run over one hour. It was decided to keep this test since according to the work done by Whitaker et al.\cite{15} the difference in loading should have little to no effect on deposition, which appears to be the case when it is compared to other favorable tests. If that test is ignored then the time for the favorable test case becomes, 56±5 min, and the loading becomes 0.11±0.01 g/m³. Another difference between the test conditions and target conditions is the mean coolant temperature during a test. While temperature has been shown to have an effect on deposition the starting temperatures are the same between test conditions. Additionally
no test was more than 3\% below the target operating temperature. A complete log of tests can be found in Appendix B.

<table>
<thead>
<tr>
<th></th>
<th>Favorable</th>
<th></th>
<th></th>
<th>Adverse</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target</td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>BFM</td>
<td>3%</td>
<td>3.01%</td>
<td>±0.008%</td>
<td>3.01%</td>
<td>±0.007%</td>
</tr>
<tr>
<td>Test Time</td>
<td>60 min</td>
<td>52 min</td>
<td>±23 min</td>
<td>64 min</td>
<td>±2 min</td>
</tr>
<tr>
<td>Coolant Temperature</td>
<td>540 °C</td>
<td>520.04 °C</td>
<td>±5.26 °C</td>
<td>534.10 °C</td>
<td>±10.25 °C</td>
</tr>
<tr>
<td>Mass Flow Reduction</td>
<td>-</td>
<td>26.50%</td>
<td>±3.65%</td>
<td>62.08%</td>
<td>±3.63%</td>
</tr>
<tr>
<td>Loading</td>
<td>-</td>
<td>0.13 g/m$^3$</td>
<td>±0.09 g/m$^3$</td>
<td>0.13 g/m$^3$</td>
<td>±0.01 g/m$^3$</td>
</tr>
</tbody>
</table>

The IR images collected from tests show that the starting conditions of the test plate were consistent. Figure 31 shows a selection of centerline sweeps from images captured at the start of tests, it is clear that there is little difference between the two cases before injection. The plate temperature fluctuates by around 40 °C from the center to edge of the plate. All the tests showed a rise in plate temperature during the test, of order 10 °C and 25 °C for the favorable and adverse conditions respectfully. This is due to the constant kiln temperature, the reduced coolant flow and the insulation of the dust deposited on the backside of the test plate.
Figure 31: Centerline Sweep of Starting IR images

Figure 32 shows a selection of images taken from several tests. These images show that regardless of small fluctuations in temperature and flowrate between tests, the physical deposition is consistent in appearance. Additionally the capture efficiency, defined earlier (Eq. 1), is consistent between tests. Moreover the capture efficiency (Table 9) shows no major dependence on turning angle, suggesting that the turning angle only affects the impact location and not the likelihood of deposition. Overall the data show that the tests are quite repeatable in both cases.
Figure 32: Repeatability Images, a) Favorable, b) Adverse

Table 9: Capture Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Favorable</th>
<th>Adverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>23.69%</td>
<td>23.04%</td>
</tr>
<tr>
<td>Range</td>
<td>±2.90%</td>
<td>±5.87%</td>
</tr>
</tbody>
</table>

Structures

In both the adverse and favorable test conditions the particle deposition form distinct structures on the inside of the test plate. These structures are on the downstream edge of the cooling hole which is to be expected as the dust has too much inertia to make the turn into the effusion hole. These structures are most obvious on the right side of the test plate (Figure 28). A small commercially available digital microscope with directional lighting was used to look at them in greater detail. Figure 33 shows the
structures that develop with a favorable turning angle. The bulk of the deposition on the plate surface in these regions forms structures in a horseshow pattern around the downstream edge of the hole with some small amount of deposition in-between holes. Additionally the beginning of deposition in the actual hole can be seen; while the structures that form on the plate are larger it is this deposition in the holes that accounts for loss of coolant flow.

Figure 33: Structures on Favorable Test
The same area of holes is shown for a plate in an adverse orientation in Figure 34. In this case the deposition has almost entirely filled the holes, again however the structure appears to have grown from the downstream edge of the effusion hole where dust deposits when the flow turns much faster that the inertia of the particles allow for. In a higher magnification image (Figure 35) it is possible to see that while mostly clogged some of these holes appear to still have a small unclogged passage; however it is unlikely that these would remain unclogged for long if the test was continued.

Figure 34: Structures on an Adverse Test
Figure 36 shows scans of the effusion holes in Figure 28, again the holes subject to edge effects should be ignored. It is possible to make out the structures noted above; however the low resolution of the laser scanner (±60 μm) makes this difficult. Because of the poor resolution it is unlikely the reported deposit heights of 150 μm in the favorable case, and 500 μm in the adverse case, are particularly accurate.
Using the OP the area around two holes was looked at in greater detail; these are shown in Figure 37 and Figure 38. These scans clearly show the shape of the buildup around the effusion holes. These scans show deposit heights of 550 μm and 360 μm for the favorable and adverse cases respectfully. The OP is a much more accurate machine,
than the laser scanner (resolution of 1 nm vs. 60 μm); because of this these scan heights are more reliable. However the measurements were taken from different test plates so that might also have affected the measured deposit height. The favorable scan (Figure 37) shows that the majority of the deposition in focused in a slight arc around the top of the effusion hole and that it drops off in height quite rapidly. While the bulk flow would be moving along the plate from bottom to top it is also possible to see the effect of lateral motion in the deposition. The effusion hole on the left is located on the centerline of the test plate and the deposits around it appear to be uniform. However the peak of the deposition on the right is clearly off center and the trail behind it appears to lean slightly to the right.

Figure 37: Optical Profilometer Scan of a Favorable Test Section
Unlike the favorable image the scan of the adverse test plate (Figure 38) shows virtually no effects of flow traveling horizontally across the scanned area. Because the deposit extends over the effusion hole it does not have the fast drop off of the deposit in the favorable case. Finally there appears to be significantly more buildup of dust away from the holes on the adverse test plate.

Figure 38: Optical Profilometer Optical Profilometer Scan of an Adverse Test Section

CFD Results

The favorable and adverse flow fields were converged using x and y velocity distributions from the PIV taken at a 4.1% and 7.7% BFMs. The 4.1% cases were chosen to match the effusion hole exit velocities and mass flow estimated from experimental
case. It was decided to match that exit velocity in the CFD, because deposition and impact location depend heavily on particle velocity which is governed by the flow speed. Eq 7 defined the Stoke number, were d is the diameter of the particle and D is the effusion hole diameter, all other values are taken from the fluid flow. The flow has a mass weighed average speed entering the effusion holes of 80 m/s in the favorable case and 88 m/2 in the adverse. This gives the favorable particles a Stokes number between 0 and 0.0012 depending on the particle diameter and the adverse stokes number between 0 and 0.0013.

\[
St = \frac{\rho Ud^2}{18 \mu D}
\] (7)
Figure 39: Flow Entering an Effusion Hole a) Favorable b) Adverse, higher speed vectors in the hole have been clipped. \( V_{in} = 2.05 \text{ m/s} \)

Two of the converged flows are shown entering an effusion hole in Figure 39, the first one is a favorable turning angle, while the second is of an adverse orientation. Once the flow is in the effusion hole there is virtually no difference between the two cases, this can be seen in Figure 40 which compares a cross section of both flows at the hole inlet.
This impingement point is on the left of the hole in the favorable case and the right side in the adverse.

![Flow Magnitude in Effusion Holes](image)

**Figure 40: Flow Magnitude in Effusion Holes**

Between different favorable and adverse solutions variations in the flow angle slightly resulted in the impingement point moving closer of further from the impingement hole. The streamlines were also consistent between the 4.1% and 7.7% solutions with the impingement location depending more on flow angle than flow speed. Examples for the favorable case of the effect of velocity can be seen in Figure 41, and the effect of flow angle in Figure 42.
Figure 41: Effect of Velocity on Flow Solution (Favorable) a) Inlet Velocity 2.84 m/s b) Inlet Velocity 1.91 m/s

Figure 42: Effect of Inlet Angle on Flow Solution (Favorable) a) Flow Angle = 20° b) Flow Angle = 75°
Impact Locations and Deposition

In each injection approximately 96000 particles, evenly distributed between sizes (1-10 μm), were simulated and no more than about 300 particles escaped without impacting the plate at least once. All of these particles were the smallest, 1.0 μm, diameter. Figure 43 show a perspective view of each plate orientation where the first impact location of each particle is displayed by number of particles. Since some cells saw over 1000 impacts the scales of the figures have been adjusted to cap at 15 impacts per cell in order to better show the shape of impacts.

Figure 43: First Impact Locations (Red ≥ more than 15 impacts) a) Favorable b) Adverse
While there are impacts on the backside surface the vast majority of the impacts in the adverse case are inside the effusion hole. The impacts in the favorable case are split between around the effusion hole and inside. When all impacts are considered there a large number of impacts that appear on the top of the effusion hole, this is shown in Figure 44.

![Figure 44: Multiple Impact Locations in Effusion Hole](image)

Like the flow solution these impact locations are fairly consistent between different inlet velocities. While the 7.7% BFM cases resulted in velocities much higher than those in the experimental conditions. Figure 45 shows the impact locations for these case and while there is substantially more dispersed impacts on the plate surface the majority of the impacts are still in the effusion hole. Moreover these impacts form the same shape in the effusion hole that are made in the lower speed simulations.
After simulated particles impact their likelihood of sticking as calculated by the deposition model, of all 96000 particles simulated about 25-30% of the particles were predicted to deposit. The histogram shown in Figure 46 shows how many of each particle diameter deposited it is obvious that the larger particles were predicted to stick more often with the likelihood of depositing decreasing as the particles shrink, there is a uptick in the likelihood of deposition for the smallest particle diameter. By using the manufacturer-provided distribution of particles sizes in ARD (Figure 15) it is possible to estimate the capture efficiency (Eq. 1) from the simulations. This is done by weighting the product of sticking and impact percentage for each particle size by the respective mass fraction of that particle size in the overall size distribution. For the favorable case
the capture efficiency was 21% and the adverse case had a capture efficiency of 19%. These capture efficiency are very similar to the 23% seen experimentally (Table 9).

![Histogram of Particle Deposition](image)

**Figure 46: Histogram of Particle Deposition**

The results of the deposition are shown in Figure 47 for each turning angle. The impacts are colored by particle size where blue is 1 μm and red is 10 μm. In both cases the only particles depositing deep inside the hole are mostly 1 μm. These are the bright red areas on the first impacts plates however these are not the areas of most deposition. Additionally the favorable case saw a large spray of deposition right outside the hole. By looking at the particles closer it can be observed that the larger particles deposited further from the hole entrance. This is indicative of the larger particles having a higher Stokes
number and too much inertia to turn with the flow and instead deposit on the backside surface. Finally all the deposits in the effusion hole are centralized on one side even though particles rebounds show impacts all over the effusion hole.

Figure 47: Simulated Particle Deposition Colored by Particle Diameter. a) Favorable b) Adverse.
The adverse case shows a similar trend to the favorable case with the larger particle impacting further away from the effusion hole. However because of the inverted geometry some of the midsized particles are depositing right inside of the effusion hole. This is where the blockage appears to start in the experimental case and then grow over the whole effusion hole. The CFD does not capture the growth of the dust because there is no two way coupling and the grid is not re meshed at any point.

Comparison

When the predicted depositions are put in a side by side comparison with the experimental data it be seen how well the CFD model anticipates deposition. Some of these comparisons are shown in Figure 48 and Figure 49. In both cases the predicted deposition looks very similar to the experimental results. In the Favorable case (Figure 48) there are a few minor differences, firstly the model predicts more deposition to either side of the effusion holes than is seen in the experimental case. Just inside the hole it can be seen that the model predicts a small number of deposits, about 3, where the experimental case shows the beginning of some flow restriction.
Figure 48: Top View of Predicted Deposition Compared to Experimental Test in a Favorable Configuration (flow and holes go from Left to Right)

The Adverse case (Figure 49) shows the beginning of buildup in the effusion hole very well. These depositions account for a large amount, if not all, of the difference in flow reduction in the adverse case. However because the grid is not adapted during the CFD simulation it is not possible to see more than the initial deposition. Other than that the predicted deposition again looks good compared to the experimental case.
Not only does the modeled surface deposition look comparable to the experimental results but so do the deposits in the effusion holes. Figure 50 shows a selection of sectioned holes and predicted deposition in the effusion holes. In the favorable case the predicted deposition in the effusion holes is slightly deeper than is seen in the experimental case. The adverse case looks more accurate as the model predicts deposition near the entrance of the effusion hole which is what is seen experimentally.
Small Particle Simulation

To better understand the deposition inside the effusion holes a second injection file with a finer distribution of particles diameters between 0.1 μm and 3 μm was made. The first thing noticed about the simulated smaller particles is the number of impacts and depositions. As was seen with the 1 – 10 μm study, small particles can escape without impacting. This is seen to a greater extent with the smaller particle study. Of the 50,000 particles 1 μm or less simulated neither case saw more than 30,000 impacts, including
rebounds, with over 90% of those above 0.7 μm. The histogram of deposits, Figure 51, shows the same increases in deposits as particle size decreases as seen in Figure 46 for <5μm. The deposition rate falls off again in the sub-micron range (<1 μm) due to the very small number of impacts. When the histogram is normalized by number of impacts (Figure 52) it becomes evident that if a small particle impacts it deposits.

Figure 51: Histogram of Small Particle Deposition
The recorded depositions of these smaller particles are shown for both turning angles in Figure 53. It is obvious how many more predicted depositions there are along the length of the effusion hole compared to the larger size range. This new size range more accurately predicts the deposition in the effusion holes when compared to the experimental cases. Also the surface deposition looks almost the same between the two cases; this suggests that the blockage in the effusion hole is governed by small particles while the deposition on the impingement surface is influenced more by larger particles. So the adverse case sees more flow blockage not because of the increased deposition in the effusion holes but because the area of deposition for the larger particles is in the mouth of the effusion hole instead of just in front of it like in the favorable case.

Figure 52: Small Particle Deposits Normalized by # of Impacts
Figure 53: Deposition of Small Particles a) Favorable b) Adverse
Summary

In addition to creating a baseline for comparison to the computational model the following dependences on flow turning angle were shown experimentally:

1. Deposit on the backside of a test coupon forms around the trailing edge of effusion holes. In the adverse turning angle this results in rapid blockage.

2. The capture efficiency of the test plates is independent of the flow turning angle.

3. Deposit forming in and blocking effusion holes has similar characteristics between turning angles.

A companion CFD study was performed using a section of the experimental models geometry and the experimental test conditions. After steady flow solutions are obtained, a particle tracking method was used that predicted concentrations of first impacts in the area where deposition is expected. Once the flow solution and particle tracking were verified a deposition model was used to predict deposition. This model was shown to closely model the deposition of the impinging flow. When small particles were simulated the model showed some reasonable prediction of the deposition in effusion holes. This deposition was made up almost entirely of 0.5-1.2 μm particles as larger particles can’t turn into the effusion hole and smaller ones follow the flow streamlines very closely and tend not to impact with the wall.
Chapter 5: Conclusion

The effects of favorable and adverse flow turning angles on deposition of single walled effusion holes for constant flow conditions at realistic combustor wall temperatures were presented. The study was divided into experimental and computational sections. In the experimental section, it was showed that the rate at which blockage occurs in the effusion holes is heavily influenced by the flow turning angle. Through sectioning test sections it was observed that while the rate of buildup may be different the actual deposition that actually causes blockage is mostly unaffected by changes in the plate orientation. Also it was observed that changes to the turning angle influenced the shape and location of dust deposits on the back side of a test coupon while not changing the overall capture efficiency of the coupon. In the Computational section, a solution was converged on the smallest repeating section of the test plate. When particles were simulated through the solution it was observed that the location of first impacts loosely matches the areas of deposition seen in the experimental case. It was shown that when a model was used to calculate deposition the model closely predicted the patterns seen in on the backside surface of the test plates.

Future Work

In an attempting to investigate the effect of turning angle on deposition and around single wall effusion cooling holes this study relied on a single stalled plenum. While this was a functional at simulating two turning sever cases of turning angle and
served to give a general picture of what is going on. Any future work performed from this study would be well served by more accurately setting the turning angle. This could be achieved either by varying the hole angle in the test plate of the incoming flow angle.

A more inclusive test matrix can also be devised to take into account the effects of attempt variable temperature, backside and flow, loading, dust combinations, or back flow margin. Through preliminary testing it was observed that these had predictable that flowed those set out in the literature, however this was never confirmed and it was never seen if the different turning angles were influenced differently by these other parameters.

Additionally the CFD simulation performed for this study was relatively simple. Any continuing work modeling this flow could be greatly improved by gridding the test plate and modeling the heat transfer through it. Other improvements include modeling a larger section of the test plate if the experimental inlet velocity can’t be smoothed out. Lastly a variable grid study could be used to gain a much better understanding of the flow after some deposition had occurred.
References


Appendix A: Plenum Temperature Correction Code

```matlab
function Tg_sph = Radiation_componsator_v2(j,STR)
    % Energy balance to correct temperature in plenum due to radiation:
    % Thermocouple can be modeled as a sphere of cylinder currently set as shear
    % note any file name tags
    extra = nargin;
    if extra == 1
        STR = '';
    end

    % Load Data
    PTH = Path_Paper( j);
    path = [PTH,STR, '.txt'];
    [TIME,PAMB,BFM,INJT,PLNT,PLTT,SLPM,DRVP,ALIT,Cd] = Loader(path, 2);

    % Calculate Pressure in plenum
    P = (PAMB+PAMB./(BFM/100))*6894.75729; %Pa

    % Temp
    T_plen  = PLNT; T_wall = PLTT;
    T_plenK = (PLNT - 32)/1.8+273; %K
    T_wallK = (PLTT - 32)/1.8+273; %K

    % Other Variables
    % Mass flow
    m_dot = SLPM*1.184/(1000*60); %kg/s

    % Area of plenum at Tcouple 1inx4in
    A = (1 * 0.0254)*(4 * 0.0254); %m^2

    % Dimensions
    d = (1/16)*0.0254; % Thermocouple diameter
    D_h = 1.6*0.0254; %
    Prim = pi * d; % m
    Len  = 1.25 * 0.0254; % m
    a = pi * (d/2)^2; % m^2

    % Sutherland's law set up
    mu_o = 1.716e-5;
    T_G = 273.11;
    S = 110.56;

    % Prandtl Number
    Pr = 0.68;

    % the conductivity of Hastelloy
    k = 70; % w / m K

    % Initial Guesses
    T_prop = T_plenK;
    crit = 1; %K

    % Iteration
    for i = 1:length(T_plen) % Loop for each Data point
        diff = 1e6;
```

85
while abs(diff) > crit % loop until convergence

% calculate air density based on previous flow temp
rho = P(i)./(287*T_prop(i));

% Calculate flow velocity previous flow temp
V = m_dot(i)./(rho*A);

% Calculate flow viscosity using Sutherlands law
mu = mu_o*(T_prop(i)/T_o)^((3/2)*(T_o+S)/(T_prop(i)+S));

% Calculate Re
Re = rho*V*d/mu;

% calculate flow Nusselt number
% sphere
mu_s = mu_o*(T_plenK(i)/T_o)^((3/2)*(T_o+S)/(T_prop(i)+S));
Nu_sph = 2 + (0.4*Re^((1/2) + 0.06*Re^((2/3)))*Pr^0.4*(mu/mu_s)^((1/4));
% cylinder
Nu_cyl = 0.911*Re^0.385*Pr^((1/3));
% duct
Nu_Dh = 4.44;

% h convection coeff
k = 6.52e-2;
h_sph = Nu_sph*k/d;
h_cyl = Nu_cyl*k/d;
h_Duct = Nu_Dh*k/D_h;

% Inner wall temp estimate
% if i >= 1
L = (1/8)*0.0254;
T_iwallK = ((k/L)*T_wallK(i) + h_Duct*T_prop(i))/(h_Duct+(k/L));
% else
%   T_iwallK = T_wallK;
% end

% Radiation Transfer
Fe = 0.85;
Fa = 1;
sigma = 5.6703*10^(-8); % w / m2K4
h_rad = sigma*Fa*Fe*(T_plenK(i)^4-T_iwallK^4).

% Compensation
% Sphere
n_sph   = sqrt((h_sph + h_rad)*Prim/(k*a));
nb_sph  = n_sph * Len;
dt_sph  = (n_sph.)/(h_sph + h_rad). * cosh(nb_sph.)./(cosh(nb_sph)-1);%
Tg_sphK(i) = (T_plenK(i)-T_iwallK)/.(dt_sph*T_plenK(i));
Tg_sph(i)  = ((9/5)*(Tg_sphK(i)-273.2)+32);

% Cylinder
% n_cyl   = sqrt((h_sph + h_rad)*Prim/(k*a));
% nb_cyl  = n_cyl * Len;
% dt_cyl  = (n_cyl.)/(h_cyl + h_rad). * cosh(nb_cyl.)./(cosh(nb_cyl)-1);%
% Tg_cylK(i) = (T_plenK(i)-T_iwallK)/.dt_cyl*T_plenK(i);
% Tg_cyl(i)  = ((9/5)*(Tg_cylK(i)-273.2)+32);

diff = Tg_sphK(i) - T_prop(i);
% diff = Tg_cylK(i) - T_prop(i);
% disp([T_prop(i), diff, i])
end
T_prop(i) = Tg_sphK(i);
% T_prop(i) = Tg_cylK(i);
Appendix B: Experimental Test Log

<table>
<thead>
<tr>
<th>Test</th>
<th>Direction</th>
<th>Starting Mass Flow (lpm)</th>
<th>Mean BPM</th>
<th>Mean Plate Temp (°C)</th>
<th>Kiln Temp (°C)</th>
<th>Particle Type</th>
<th>Mean Air Temp (°C)</th>
<th>Kiln Temp Reduction</th>
<th>Injection Time (min)</th>
<th>Mass Flow Reduction</th>
<th>Captured Weight</th>
<th>Capture Efficiency</th>
<th>Loading (g/m^23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>0.0020</td>
<td>3.01%</td>
<td>-</td>
<td>517</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>29</td>
<td>30.15%</td>
<td>0.1723</td>
<td>26.51%</td>
<td>0.22</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>0.0021</td>
<td>3.02%</td>
<td>-</td>
<td>525</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>54</td>
<td>25.31%</td>
<td>0.1432</td>
<td>22.03%</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0.0021</td>
<td>3.01%</td>
<td>-</td>
<td>529</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>63</td>
<td>63.60%</td>
<td>0.1860</td>
<td>28.62%</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>0.0021</td>
<td>3.01%</td>
<td>-</td>
<td>540</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>65</td>
<td>64.33%</td>
<td>0.1476</td>
<td>22.71%</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>0.0021</td>
<td>3.01%</td>
<td>-</td>
<td>515</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>57</td>
<td>27.64%</td>
<td>0.1470</td>
<td>22.62%</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>0.0019</td>
<td>3.01%</td>
<td>-</td>
<td>529</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>66</td>
<td>63.26%</td>
<td>0.1374</td>
<td>21.14%</td>
<td>0.13</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>0.0020</td>
<td>3.01%</td>
<td>-</td>
<td>519</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>58</td>
<td>26.39%</td>
<td>0.1650</td>
<td>25.38%</td>
<td>0.11</td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>0.0021</td>
<td>3.01%</td>
<td>-</td>
<td>526</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>61</td>
<td>58.44%</td>
<td>0.1116</td>
<td>17.17%</td>
<td>0.13</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>0.0020</td>
<td>2.98%</td>
<td>-</td>
<td>509</td>
<td>982</td>
<td>Volcanic Ash &lt;25</td>
<td>1.00</td>
<td>53</td>
<td>0.00%</td>
<td>0.0927</td>
<td>9.27%</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>0.0021</td>
<td>3.01%</td>
<td>866</td>
<td>522</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>51</td>
<td>25.49%</td>
<td>0.1614</td>
<td>24.83%</td>
<td>0.12</td>
</tr>
<tr>
<td>Test</td>
<td>Direction</td>
<td>Starting Mass Flow (lbm/s)</td>
<td>Mean BPM</td>
<td>Mean Plate Temp (C)</td>
<td>Kiln Temp (C)</td>
<td>Particle Type</td>
<td>Mass Injected (g)</td>
<td>Injection Time (min)</td>
<td>Mass Flow Reduction</td>
<td>Captured Weight</td>
<td>Capture Efficiency</td>
<td>Loading (g/m³)</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>-----------------------------</td>
<td>---------</td>
<td>---------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>----------------</td>
<td>------------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>A</td>
<td>0.0020</td>
<td>3.02%</td>
<td>881</td>
<td>536</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>65</td>
<td>58.99%</td>
<td>0.2071</td>
<td>31.86%</td>
<td>0.12</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>0.0021</td>
<td>3.02%</td>
<td>864</td>
<td>522</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>60</td>
<td>24.04%</td>
<td>0.1352</td>
<td>20.80%</td>
<td>0.09</td>
</tr>
<tr>
<td>13</td>
<td>A</td>
<td>0.0020</td>
<td>3.01%</td>
<td>881</td>
<td>544</td>
<td>982</td>
<td>0-10 ARD</td>
<td>0.65</td>
<td>61</td>
<td>63.82%</td>
<td>0.1861</td>
<td>28.63%</td>
<td>0.12</td>
</tr>
</tbody>
</table>