The Effect of Particle Size on Deposition in an Effusion Cooling Geometry

Thesis

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

By

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2018

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Abstract

The effect of particle size on particle accumulation within an effusion cooling geometry common to gas turbines was investigated experimentally and computationally. A flat plate with an effusion cooling hole array based on a gas turbine combustor liner was subjected to particulate laden flow in an accelerated deposition facility. The tests were conducted at an engine relevant plate temperature of 1118 K, coolant temperature of 950 K, and held at a constant pressure ratio of 1.03 (cavity to ambient). To elucidate the effect of particle size, six unique size distributions of Arizona Road Dust (ARD) smaller than 20 micron were introduced to the flow independently. Experiments were also conducted in which two different dust size distributions were sequentially delivered to the test article. These experiments clearly indicate that the smallest particles within the range tested accumulate within the hole creating deposit structures and blocking the effusion holes. They also indicate that larger particles within this range can have an erosive effect on the deposit structures as they build, changing the structure's morphology and blockage behavior.

Computational fluid domains were developed to replicate the test article geometry before and after a test to investigate the effect that deposit structures have on deposition. Particles were introduced to these domains after reaching a steady solution and were tracked through the solution with a Lagrangian trajectory solver. The impact locations of

the particles were recorded and a particle sticking model was employed to determine if the particles stick or rebound. The domain with the clean hole showed that the smallest particles impact and were prone to sticking in the area where deposits form experimentally. As the particles increase in size, the number of impacts and likelihood of sticking decreased. The domain with scoop deposit structures showed that these structures can change the particle impact trajectories influencing the buildup process.

Overall, this body of work shows that particle size distribution has a first order effect on the blockage caused by particle deposition in effusion cooling geometries. The observation that 0.5-3 μm particles are primarily responsible for blockage while large particles can reduce deposit structure size highlights the complexity of particle deposition. This has significant implications for future work, particularly high fidelity modeling.

Acknowledgments

In the last seven years of my academic career, I've lived in three states, attended two universities, and have been shaped by countless influences resulting in this one body of work. My parents, siblings, and friends have been boundless sources of encouragement and steadfast pillars of support without which I would not be who I am. I can't thank them enough for everything they have done.

Few people have been as influential academically as my advisor Dr. Bons. His guidance and expertise have been invaluable assets during my time at OSU. He has pushed me beyond what I thought I was capable of, allowing me to grow into a better researcher and person. Likewise, I'd like to thank my lab mates and friends who have created an environment that I could thrive in. They have turned daunting and difficult tasks into manageable experiences. I would like to thank Steven Whitaker for being a mentor to me in the lab during my first year and being a source of advice and knowledge in this research area. I would also like to thank Chris Bowen, Lucas Agricola, Ryan Lundgreen, and Will Banks for helping me learn how to run simulations in Star CCM+ and answering any questions I had.

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Chapter 1. Introduction

1.1: Motivation

The modern gas turbine is an engine prized for its high power output and thermal efficiency while being relatively light weight and able to use a large variety of fuels. Due to its versatility, the gas turbine engine is utilized in a range of industries, from land based power plants to aviation. As fuel prices increase and emissions become a larger environmental concern, the efficiency of an engine stands as a primary design consideration. One is able to increase a gas turbine's efficiency thermodynamically by increasing the pressure in the combustor and thus the overall compression ratio. The increased pressure allows for higher turbine inlet temperatures which increases thermodynamic efficiency. Since the conception of the gas turbine, an upwards trend in turbine inlet temperatures has been seen and is shown in Figure 1 [1]. As turbine inlet temperatures have increased, the melting temperature of components in the turbine section have been approached. In order to protect the metal components, internal and external cooling methods such as impingement cooling, internal convection cooling, and film cooling have been devised. All of these cooling schemes utilize air that is bled from the high pressure compressor.

Figure 1: Turbine Inlet Temperature over Time [1]

Jets of fluid impinging on a surface are well known for having high heat transfer behavior. Impingement cooling schemes utilize this characteristic by impinging coolant jets on the backside of the hot section components, cooling the metal. Convection cooling takes coolant and passes it through the internal channels of the component. This cools the channel surfaces and can be augmented by putting ribs and/or pins in the channels. Film cooling takes coolant from an internal cavity and directs it through holes in the component's walls. Convection occurs as the coolant flows through the cooling hole, decreasing the metal temperature. Once the coolant reaches the exterior of the component, it creates a protective film over the part. This discourages the hot gas stream from directly interacting with the exterior surface. An example of a generic turbine blade with these cooling schemes can be seen in Figure 2 [2].

Figure 2: Generic Cooling Scheme [2]

If a gas turbine is exposed to an environment where the air is laden with particulate matter, the particulate matter can make its way to these cooling schemes. The particulate can deposit within the internal cooling schemes and reduce the cooling effectiveness. This results in an increase the metal temperature which can lead to reduced part life or catastrophic failure such as is seen in Figure 3 [3]. With the increased use of gas turbines worldwide, this becomes a larger concern as gas turbines are exposed to a wider range of environments such as deserts or highly polluted cities.

Figure 3: Turbine Blade Damage from Deposition [3]

1.2: Review of Experimental Studies

Over the past decades a significant amount of work has gone into experimentally investigating the effect deposition has on cooling schemes as well as the parameters that most strongly affect deposition behavior. Full scale experiments where dust is intentionally introduced to an operating gas turbine offer the most realistic experiment because all of the related physics are represented. Dunn [3] describes some of these experiments in detail and concludes that ingested dust damages not only the hot section but also the compressor, oil system, and any passengers who may inhale the dust. Impacting dust can damage the compressor airfoils, reducing aerodynamic performance. These impacts can also break the dust up into smaller particles. In two different

experiments, dust taken from the compressor bleed was smaller than the dust initially injected. Dust taken from the same experiment at the 5th compressor stage had a mean particle size of 8 μm while the dust taken from the 9th compressor stage had an average particle size of 3.5 μm . In the hot section, deposition on the component surfaces and in the cooling holes can increase metal temperature leading to the damage seen in Figure 3. The down side to full scale experiments is that they are expensive, difficult to conduct, and may not be able to be released to the public.

In order to alleviate some of the cost and difficulty, component level testing has become a common practice. Kim et al. [4] review the results of four studies that used hot section test systems from engine hardware without the rest of the engine. The experiments used two types of volcanic materials as their ingested particulate. The volcanic material was mixed into compressed air which was fed to a combustor. The combustor heated the seeded air and exhausted it to inlet guide vanes, two of which were cooled independently of the others in order to see the effects of vane metal temperature on deposition. The experiments showed that the amount of deposited dust depended primarily on the type of dust injected, concentration of dust injected, turbine inlet temperature, and vane metal temperature. Deposits were seen to build up in regions of flow deceleration and could block cooling holes, which decreased cooling effectiveness. In some cases, the deposits may have caused the metal temperature to increase and caused parts to melt.

In most scenarios, the deposits grow over thousands of flight hours. Since this is an unrealistic time frame for experimentation, accelerated deposition facilities have become

necessary. Validating such an approach, Jensen et al. [5] showed that accelerated deposition tests can closely match the surface topology and chemical composition of deposit found on turbine blades that have been in service. Further isolating individual components, CFM56-B nozzle guide vanes (NGV) were held in a Turbine Reacting Flow Rig (TuRFR). Bonilla et al. [6] used fly ash to investigate the effects that particle size and the amount of film cooling have on deposition on the external surfaces of the NGVs. Important controlled parameters in the test include the hot gas temperature, Mach number of the hot gas, and Stokes number of the particulate. The results of this test show that deposit thickness depended primarily on Stokes number and the amount of film cooling. It was seen that particles with a larger Stokes number, or larger diameter, were more likely to stick than particles with a smaller Stokes number. The deposits formed mainly on the leading edge of the vane and propagated down the pressure side of the vane. Without cooling, deposits made it to 60% chord while with high film cooling the deposit only made it to 40% chord. This was attributed to the film cooling solidifying the particulate and causing it to rebound off the surface instead of depositing.

Using the same facility, Webb et al. [7] conducted a similar study using four different coal ashes. They found that deposition growth had a first order sensitivity to the gas temperature. Composition of the coal was also found to have a first order effect on deposition. Film cooling was seen to significantly affect the deposit thickness for some of the ash samples but had almost no effect on others. They hypothesized that the film cooling lowered the vane metal temperature below the melting temperature of bituminous fly ash which prevented deposit growth. The same film cooling wasn't able to lower the

vane metal temperature enough for other ash samples and thus the other samples were seen to grow. This suggests that chemical composition is an important factor in deposition.

Reaching temperatures similar to those found at the inlet of a turbine can be difficult in single component test facilities. In facilities designed to test NGVs, similar to the TuRFR facility, inlet flow temperatures near 1620 K were achievable. Without cooling provided to the NGV and at an inlet temperature of 1373 K, it was seen that fly ash deposited along the pressure side of the vane. Arizona Road Dust (ARD) with a particle diameter range of 0-5 μm was also delivered to a vane at the same conditions. This dust also covered the pressure side of the vane and became completely glassified [8].

Lowering the vane temperature by providing cooling prevented the ARD from melting at the leading edge. At higher inlet temperatures, the leading edge deposits grew in size and appeared to flow like a liquid before hardening.

Song et al. [9] specifically looked at the melting temperatures of different volcanic ash samples and compared them to standard sand test dusts. Using a heating microscope, they were able to watch as cylindrical samples of dust melted in a small furnace. They determined that both the size of the particles as well as the chemical composition play a large role in the melting temperature of the samples. They concluded that sand based dusts do not have the same melting behavior as volcanic ash, and thus for experiments attempting to match deposits seen on hardware that has flown through ash clouds, sand cannot be substituted.

1.2.1: Impingement-Effusion Studies

The leading edges of NGVs experience some of the highest temperatures in a gas turbine and thus require substantial cooling. Jet impingement cooling on the inlet side of a film cooling scheme is often used to achieve this level of cooling. As a result, the effects of particles depositing on the internal structure of the cooling schemes is a topic of interest. It's important to distinguish between internal and external deposition because they don't necessarily share the same dependencies. The work described above dealing with deposition on NGV is all considered external deposition while the work reviewed here after will deal with internal deposition.

In the open literature, impingement-film cooling deposition experiments can be separated into two groups, parallel plate studies and concentric cylinder studies. There are advantages and disadvantages to each method used. Parallel plates are an easier geometry to work with and can be modified with ease to conduct parametric studies. Unfortunately, they lack the effects that curvature may have on the particle trajectories. The concentric cylinders more accurately simulate the geometry of a NGV's leading edge but are more difficult to post-process and modify for testing the dependency on cooling geometry.

One parallel plate impingement-film cooling study was conducted by Land et al. [10] which investigated the effects of pressure ratio, mass of particulate delivered, particle size, and cooling scheme geometry. They defined a flow parameter that depended on mass flow rate and pressure which non-dimensionalized momentum and pressure forces. Comparing the flow parameter before and after dust injection allowed them to quantify a percent reduction in flow parameter associated with particle blockage. They

found a non-monotonic trend in reduction with pressure ratio. This was explained that at low pressure ratios the dust blocked the impingement plate while at the higher pressure ratios the dust was more fully entrained in the flow and blocked the effusion holes. Reduction in flow parameter was seen to increase with mass of dust delivered and particle size. Looking at the hole geometry, a staggered arrangement of impingement to effusion holes was found to have lower reduction behavior compared to an aligned arrangement over all the pressure ratios investigated. Additionally, the distance between the plates was found to also have a first order effect on flow parameter reduction. For both hole arrangements, a distance three times that of the impingement hole diameter ($S/D_i = 3$) had the lowest reduction with the staggered arrangement having lower reduction than the aligned arrangement. Interestingly, the difference in reduction behavior between the two hole arrangements disappeared when S/D_i became 1.1 and 6.

Another study using the same facility looked at the effects of cooling hole size, cooling hole area of both plates, hole arrangement, and temperature. It was found that the lowest reduction in flow parameter occurred when the impingement hole area was large and the highest blockage when the film cooling hole area was small [11]. They found that blockage decreased monotonically by increasing impingement flow area. ARD in a range of 0.6-3000 μm was used in these experiments and the total particulate mass delivered was found to be proportional with reduction which agreed well with their colleagues' findings [10]. Temperature of the particles and the plate had independent effects on flow parameter reduction. It was seen that reduction increased non-linearly over the film cooling plate temperature range of ambient to 1255 K. Increasing the particle temperature

at the same coolant temperature increased the non-linear behavior seen with plate temperature. This indicates that the dust's adhesion characteristics have a temperature dependency in this range of temperatures.

Clum et al. [12] tested flat impingement-film cooling geometries in an accelerated deposition facility that independently heated coolant and the back side of the film cooling plate. An important parameter they used to quantify deposition is the capture efficiency of a configuration which is the ratio of the dust collected on a plate and the mass of dust injected. They found that increasing the coolant temperature had the effect of increasing both the capture efficiency and height of the cone structures that formed under the impingement holes. For an internal cooling geometry like this, they found that particles with the same composition but lower Stokes number were more likely to be captured. This is in contrast with the trend seen in external deposition where particles with larger Stokes number are more likely to stick [6]. Transient tests were conducted and video was taken of the cone structures as they formed. This showed that the basic cone shape was constant up to a point at which they became more peaked. It also illuminated the fact that the cone structures could break off the plate and be redeposited in recirculation regions. They also saw that due to aerodynamic lensing, the base of the cones could be up to twice the diameter of the impinging hole.

All of the component and cooling scheme tests thus far discussed were conducted at ambient pressure. Some may have looked at the pressure ratio across the cooling scheme but it was exhausted to ambient and so any effect absolute pressure has on deposition is ignored. Sacco et al. [13] constructed a high pressure facility to look at the

independent effects that absolute pressure and temperature had on an impinging flow. They found that by increasing absolute pressure at a constant temperature and pressure ratio, the capture efficiency of the target plate and the size of the cones that formed decreased. Increasing temperature increased the capture efficiency but the trend with pressure remained the same. The effects of pressure were described in three ways. The first was that as pressure increases the fluid density, Reynolds number (Re_d), and in turn the drag on the particles increases. As the drag increases due to the increase in density, the particles will more closely follow the streamlines and avoid hitting the plate. Pressure was also seen to influence fluid shear and the discharge coefficient through the orifice plate. Due to the difficulty of backside heating in an enclosed pressure vessel, most accelerated deposition facilities operate at ambient pressure. This must be kept in mind when comparing accelerated deposition results to hardware seen in the field.

In order to better simulate the leading edge of a nozzle guide vane, three studies have been reported in the open literature using concentric cylinders with an impingement-film cooling scheme. The first looked at the effects of particle concentration, particle size, and flow temperature. It was seen that flow blockage was weakly dependent on particle concentration over two orders of magnitude at ambient temperature. This dependency decreased as the flow temperature increased. Looking at three different size distributions of ARD over a range of 0-20 μm they found that the smallest particles had the tendency to agglomerate into clumps and likely caused increased blockage. It was seen in the larger particle size distributions that larger particles caused less blockage [14].

The second study also looked at these same parameters but higher flow temperatures [15]. Experiments were conducted using four different size distributions of ARD within the range of 0-20 μm . At flow temperatures of 300 K and 833 K, it was seen that the level of blockage remained constant over a large range of particulate concentration where a loading rate is the mass of particulate per cubic meter of air. An engine in operation will see a low loading rate of dust over many flight hours. The finding that blockage is not dependent on loading gives confidence that accelerated deposition tests adequately replicate the deposition process in gas turbine operations. A marked increase in flow blockage was seen at the experiments done at high flow temperatures. This was an interesting result because over the range investigated, 700-866 K, the dust is well below the melting temperatures as had been seen in some of the external deposition tests. Particle size was seen to have two distinct impacts on deposit growth. It was shown that size distributions with more particulate mass below 3.25 μm created more flow blockage and that this size was primarily responsible for creating blockage. The particles larger than 5 μm had the opposite effect. These particles had an erosive effect on the particle deposits which helped prevent deposit growth and even reduced the size of existing structures.

Using the same test article used above but inside an electric kiln, Whitaker et al. [16] were able to examine the effects that surface temperature has on deposition. It was seen that the level of flow blockage increased linearly with the external temperature of the test article. Interestingly, the deposits created shell like structures on the impingement holes which were deemed primarily responsible for flow blockage. Since access to the

temperature of the impingement cylinder was not possible, a companion computational fluid dynamics (CFD) study was conducted to further investigate the effects of temperature. The CFD showed that the flow temperature was weakly affected by changing the external metal temperature, but the surfaces of the metal components were strongly affected by increasing the external temperature of the effusion cylinder. Although not modeled, the deposit structures that build on the cylinders would likely also be at the higher temperatures as well which would encourage further deposit formation. Particles were injected into the solution and sticking was predicted using a particle deposition model in the open literature in order to see where particles impact and stick. It was seen that small particles stick just downstream of the impingement holes which is where the shell structures are seen experimentally.

1.2.2: Film Cooling Studies

Film cooling is another active area of research in the heat transfer community. When a film cooling design is bombarded by particulate, three events can occur. The best case is when the particulate simply rebounds off the surface without causing damage. It can also impact the surface causing erosion or spallation of the surface. The particulate can also stick to the surface, creating deposit structures and possibly blocking the film cooling holes. A study by Sundaram et al. [17] looked at the latter two cases on an endwall of two scaled up passages of a first stage vane. A constant temperature difference of 40 K between the coolant and main flow was held during the test as measured by thermocouple rakes. Temperature measurements of the vane surface were captured using

an infrared (IR) camera which was calibrated using thermocouples at different locations. To match realistic end wall surface distortions, the vanes were covered in sand paper and different deposit structures were installed near the film cooling holes. Semi-elliptical end wall deposits of varying minor radii were used to simulate hole blockages and covered with sand paper to represent scaled up surface roughness. To simulate spallation, some sand paper was removed downstream of the film hole. Results from this study showed that the external deposit's effect on cooling effectiveness depended on position and height of the deposit structures. For the case that the height was less than half a hole diameter, cooling effectiveness was reduced between cooling rows but increased along the endwall-vane junction. When this height was increased, cooling effectiveness was reduced everywhere. The deposits in the film cooling holes reduced mass flow through the hole and reduced cooling effectiveness dramatically. Spallation was seen to have little effect on cooling effectiveness.

Due to the high temperature melting points of most test dusts, studying the deposition behavior and effects of molten particulate can be a challenge. Lawson et al. [18] simulated molten and solid particulate deposition in a low speed wind tunnel using wax droplets. Air seeded with molten wax flowed over a row of film cooling holes that were supplied by an independent and cooler source of air. Wax injection happened in cycles at each momentum flux ratio investigated and pictures were taken with an IR camera as well as a digital camera in order to get a history of deposition growth. The results indicate that for momentum flux ratios of 0.23 and 0.5, cooling effectiveness was reduced by 20% after eight cycles while for a momentum flux ratio of 0.95 the cooling

effectiveness was reduced by 6%. This was explained that for the high momentum flux ratio, the flow had already separated and inhibited cooling effectiveness to begin with.

Another study looked at the effect that film cooling holes had on external deposit location. A flat Inconel alloy test coupon with film cooling holes was exposed to a hot gas path laden with coal fly ash. It was found that the capture efficiency of the tested coupons decreased as the blowing ratio of the cylindrical cooling holes increased. Fan shaped holes prevented ash from depositing downstream of the holes and had a lower capture efficiency of the ash than cylindrical holes. Coupons with the same hole configurations but with thermal barrier coatings (TBC) were also tested. It was found that the TBC coated coupons had an order of magnitude greater capture efficiency than the bare coupons. Interestingly, coupon temperature uniformity decreased as deposit height increased. Areas with thick deposit showed increased surface temperature. This had a cascading effect in that the higher temperature deposits were able to capture incoming particles more effectively. This increased the deposit thickness which increased the surface temperature of the deposit. [19]

The effects of particle size, temperature, and flow area in a cylindrical film cooling geometry have also been investigated. The test article was heated inside an electric kiln to control the external surface temperature while a double by-pass heater controlled the coolant temperature. The flow parameter before and after dust injection was compared to determine the level of blockage in each test. ISO 12103-1, which has a similar chemical composition to ARD, was used in three dust size distributions that had mass mean diameters of 18.5, 37.3 and 50 μm . The dust was injected en masse through

an eductor which helped entrain the dust in the coolant flow. It was seen that the larger dust size distributions caused greater blockage for the same amount of dust mass injected. For all of the dusts investigated, the blockage levels increased when more mass was delivered. Varying the metal surface and coolant temperatures allowed the effects of each to be studied independent of each other. Deposition was shown to have a greater sensitivity to the metal temperature than the coolant temperature with some of the dust melting in the high metal temperature tests. Increasing the number of cooling holes, and thus increasing flow area, was seen to reduce the level of blockage in the cylinder. This was ascribed to an increase of the inlet velocity. The effect of the pressure ratio across the film holes was also investigated. It was seen that by increasing the pressure ratio over the range of 1.1 to 1.6 the same amount of dust would generate less blockage. [20]

The amount of turning that particles have to make in order to exit a film cooling hole also has an influence on deposition. Blunt et al. [21] used a flat film cooling plate in an electric kiln to test the effects that turning angle has on deposition. A stalled diffuser was used to set up a flow that approached the test coupon at an angle. The test coupon had a set inclination angle for the holes. By turning the plate 180° , the effect of more aggressive turning could be studied. A 0-10 μm range of ARD was used to generate the flow blockage. It was seen in both cases that the dust deposited on the leeward side of the hole. In the favorable (low turning angle) case, the leeward edge is past the hole while in the adverse (high turning angle) case, the leeward edge corresponded to the inlet of the hole. Both orientations captured a similar amount of dust, but the adverse case was seen to have over twice as much flow blockage for the same amount of dust delivered. This

means that the location of the deposit had a significant impact on the amount of blockage that was created. A companion CFD study looked at a section of the experimental geometry. Particles were injected into the flow and tracked through the solution with an Eulerian-Lagrangian solver. Impact locations were recorded and showed good agreement with experimental deposit location. It showed that the smallest particles could deposit along the entire length of the hole while the larger particles tended to impact on the plate surface.

1.3: Review of Numerical Studies

Numerical solutions to film cooling heat transfer have been an active area of research for more than 20 years. Often times the studies focus on the flow through the film cooling holes and the complex fluid structures that develop on the external plate surface [22]. These can be used to supplement experiments and enhance understanding of the underlying physics at play. This can help to validate correlations and lay the ground work for more complex models that can remove the need for meshing the cooling hole geometries, saving computational resources [23, 24]. Numerical studies also can aid in understanding the effects that particle deposition can have on film cooling.

1.3.1: Deposit Effect on Film Cooling

Cheng et al. [25] conducted a numerical investigation of the effects that deposition location and blowing ratio have on film cooling effectiveness using Fluent. The fluid domains had a plenumized source which supplied three cooling holes that exhausted to a hot crossflow. Hole blockage was simulated by placing a tetrahedron on

the leading edge, side, or trailing edge of the cooling holes at either the hole inlet, middle section, or hole outlet. A Reynolds-Averaged Navier-Stokes (RANS) solution was found using a realizable k - ϵ turbulence model for each geometry. It was found that the deposit on the leading edge of the hole outlet increased the cooling effectiveness compared to a straight hole without blockage. This deposit reduced the effects of the vortices caused by the jet interaction with primary flow. Coolant didn't penetrate into the crossflow as deeply but had an increased streamwise velocity. This increased the film cooling effectiveness especially at high blowing ratios. When the deposit was located at the outlet trailing or lateral edges, the film-cooling effectiveness suffered. The deposits at the inlet and the middle of the cooling hole also reduced the film-cooling effectiveness but only for the higher blowing ratio cases.

Another study looked at the size as well as the location of a deposit using a similar geometry as used by Cheng et al. Instead of using tetrahedral blockages, hemispherical blockages of varying diameter were used [26]. RANS simulations were conducted using a realizable k - ϵ turbulence model in order to accurately model the film-cooling heat transfer. It was shown that by increasing the diameter of the hemispherical blockages, and thus increasing the amount the hole is blocked, the area the coolant air can cover decreases. This decreases the lateral film cooling effectiveness. Deposit location within the hole itself didn't seem to have a strong effect on the film cooling effectiveness.

1.3.2: Modeling Deposition

Although studies of arbitrary hole and deposit geometry can aid in understanding basic parametric relationships, they don't provide a tool for engine designers to evaluate a

cooling feature's susceptibility to blockage. In recent years, much effort has been put into developing generalized deposition models that can be implemented alongside commercial CFD software. The goal of modeling deposition in this way is to provide a tool to help predict deposition on theoretical and existing hardware. This allows engineers to take deposition into consideration during the design process with the aim to reduce the effects that blockage may have, thus increasing part life and component durability. It can also be used for visualizing how existing hardware will behave when supplied with particulate laden air. This could be useful for understanding why part failures are occurring or assessing how existing designs will fare in new markets.

The first models used alongside numerical flow investigations focused on a critical velocity of a particle as it hits the surface of a component. If the particle was below this critical velocity then the particle wouldn't have the energy to rebound and thus stuck to the surface [27]. At high temperatures, a particle no longer can be considered completely solid and has viscoelastic properties. In order to capture this, as well as sensitize deposition to high temperatures, a critical viscosity model was proposed that defined the probability of a particle sticking based on the viscosity of a particle [28]. Barker et al. [29] compared these two models against experimental accelerated deposition tests on nozzle guide vanes. They found that the Eulerian-Lagrangian particle tracking technique predicted particle impacts in areas that had high deposition rates in experiments. The critical velocity model was seen to predict more sticking than the critical viscosity model. Both models presented fundamental weaknesses such as dependencies on unknown material properties that change the sticking predictions. They

both are only valid for initial deposition and were found to be lacking in the ability to predict large scale deposition.

A physics based model proposed by Yu and Tafti [30] treats each particle as a sphere impacting a flat surface. The spheres have an initial incoming kinetic energy with which it can rebound off the flat surface. The impact is treated using Hertzian impact theory. Energy losses during impact are calculated by modeling the compression of the sphere, surface dissipation, and work from adhesion. The material properties of the spheres are sensitized to temperature and particle size by using experimental data in the open literature. Taking the losses into consideration, a coefficient of restitution (CoR) is determined and rebounds are predicted. If CoR is 0 then the particle sticks. This model was shown to agree reasonably well with CoR experiments conducted with ARD impacting a stainless steel plate.

In order to reduce complexity and necessary computation time, Bons et al. [31] presented a model, dubbed the OSU deposition model, written in algebraic form that could be implemented as a user defined function in commercial CFD software. They treated the particles as cylinders that acted as one-dimensional springs in compression. The cylinders elastically store energy until yielding occurs, then the remaining kinetic energy is dissipated through plastic deformation. Subtracting the work of adhesion from the stored elastic energy and adding a rolling moment caused by drag, the normal CoR is determined. They compared the model against existing data finding good agreement with some tuning of material properties and sensitization to impact angle. The authors note

that this model can be improved by including the effects of erosion and dynamically changing the surface in a simulation to reflect deposit build up.

The OSU deposition model has been used to provide insight into particle impact and sticking locations [16, 21]. Forsyth et al. [32] introduced a dynamic mesh morphing (DMM) technique that changes the fluid domain to account for particles depositing on a surface. They tracked particles through a converged solution using an Eulerian-Lagrangian solver with continuous random walk and recorded impact locations. The OSU deposition model was used to determine the particles' sticking and rebound behavior. They found that for an impingement flow, the structures that developed in the simulation qualitatively matched structures seen experimentally. Since the deposition model is dependent on difficult to find material properties, the model wasn't able to accurately recreate the deposit growth rate but performed better than previously suggested models. Similar results were seen in a film-cooling geometry. Deposit size and shape were over predicted in this case which may be due to the lack of an erosion component to the model or possibly an over estimation of deposition of oblique impacts. This showed promising results for using DMM in the future and highlighted the need for a better understanding of particle material properties.

To better inform the current models, Whitaker [33] compared experimental CoR results using a range of particle types and temperatures against predicted CoR from different models. He found that the models lacked the fidelity desired for accurate prediction but by incorporating a velocity dependency to yield stress and randomness to the rebounds, the predictions matched the experimental data better. Using the OSU

deposition model with the proposed updates, the elastic modulus of the particles could then be sensitized to temperature if a temperature dependency was not readily available. The original model was then compared with the modified model for a general impinging flow. The modified model more accurately predicted CoR with respect to experimental data found in the literature. Bowen et al. [34] also looked at a simple impinging flow with the OSU deposition model. The adhesion properties of particles are difficult to assess or find data for but none the less are an important part of these models. They found that an iterative process can be used to tune these adhesion properties and make them sensitive to temperature. The best results were found when DMM was part of the iteration because the cone structures that built up changed the flow field. Both of these studies present ways of improving existing models and indicate that more work is needed to fully capture the physics of deposition.

Chapter 2. Experimental Methods

2.1: Test Facility and Instrumentation

Deposition experiments on a full gas turbine engine are a cost, time, and resource intensive endeavor to be avoided if possible. An accelerated deposition facility was constructed at The Ohio State University Aerospace Research Center in order to test a representative cooling geometry at engine relevant conditions without the requirement of testing an actual engine. This allows for faster and cheaper tests to be run while investigating the fundamental physics of deposition. A schematic of the facility is shown in Figure 4 and consists of four parts: coolant preheating, a dust delivery system, the test fixture/article, and an electric kiln.

Figure 4: Test Facility Schematic

Air is supplied to the coolant preheating section from compressed shop air. The air is regulated down from 620 kPa to 413 kPa prior to entering the system. The mass flow through the facility is set during a test by an Alicat Scientific 0-100 SLPM (standard liters per minute) mass flow controller. The controller has an accuracy of $\pm 0.8\%$ of the reading plus 0.2% of the full scale reading. For a typical test, this translates to $\pm (0.2 + 0.8)$ SLPM which is approximately 1% of the mass flow set point. SLPM is a method of measuring mass flow rate and can be converted into kg/s using the standard density of air based on standard temperature (298 K) and pressure (101.325 kPa) using the following relation.

$$\left[\frac{kg}{s} \right] = \frac{SLPM * 1.184}{60000} \quad 1$$

The air then goes through a 6 kW Sylvania serpentine inline heater exchanger. A 1.58mm diameter K-type thermocouple immediately downstream of the heat exchanger measures the flow temperature and is used to control the level of preheating the coolant receives.

A conveyor belt dust injection system controls the rate at which dust is introduced to the flow. The motivation for this type of feed system is discussed in detail by Peterson [14] in which a similar feed system was constructed. The system has a 280 mm conveyor belt driven by a stepper motor through two gear boxes with a total speed reduction of 1800:1. This large speed reduction allows for fine control over the conveyor belt speed and thus the rate of particle injection. Dust that is loaded onto the conveyor belt drops into a funnel and down a drop tube into the main gas path. In order to prevent backflow into the dust injection system, the conveyor belt system is housed in a welded aluminum

box with a removable acrylic top. The top must be removed when dust is loaded onto the conveyor belt. The top has a rubber gasket along the edges and is clamped onto the aluminum box during a test so that the pressure within the dust injection system can come to equilibrium with the main gas path. Additionally, 1 SLPM of air is provided to the box to further prevent backflow in case a small leak develops during a test. Figure 5 shows the feed box and all of its components.

Figure 5: Dust Feed Box

Once the dust passes through the drop tube, it mixes with the preheated coolant along a 0.53 m equilibrium tube. All surfaces along the main gas path, starting at the inline heater and ending at the exit of the equilibrium tube, are insulated to prevent heat loss. A long equilibrium tube was designed to allow the dust to come up to speed and temperature with the main gas path as well as to create distance between the conveyor dust injection system and the kiln. To determine if the particles are coming up to speed and temperature with the main flow path, a simplified particle physics simulation and

thermal analysis was performed. Particles starting at rest and ambient temperature were injected into the experimental crossflow. The crossflow had an average velocity of 40.6 m/s and a static temperature of 950 K which represents the experimental conditions. Using a drag coefficient correlation from White [35], shown in Equation 2, a simple force balance was constructed to determine the instantaneous acceleration of the particles and was integrated to determine velocity and distance traveled.

$$C_D = \frac{24}{Re_d} + \frac{6}{1 + \sqrt{Re_d}} + 0.4 \quad 2$$

Then the particle Nusselt number was found using a correlation from Bergman [36], seen in Equation 3. Using a lumped capacitance model, a particle's change in temperature through the flow could be estimated. The flow and thermal models were iterated in time to determine the dynamic thermal and velocity behavior. The simulations were concluded when the particles were within 1 K of the flow temperature.

$$\overline{Nu_d} = 2 + (0.4Re_d^{1/2} + 0.06Re_d^{2/3})Pr^{0.4} \left(\frac{\mu}{\mu_p} \right)^{1/4} \quad 3$$

In all the calculations, the Reynolds number was based on the particle slip velocity and the particle diameter. The viscosity term μ_p is defined as the air viscosity at the temperature of the particle. Five particles were looked at in this quick study ranging from 1 μm to 20 μm . Figure 6 shows the non-dimensional temperature as the particle passes through the equilibrium tube and Figure 7 plots the particle velocity over the same distance. From these plots, it is apparent that particles less than 10 μm reach flow conditions within 10 cm while particles up to 20 μm reach flow conditions within 35 cm. A maximum Biot number 0.18 occurs at the beginning of the injection and quickly falls

below 0.1. This indicates that a lumped capacitance assumption is valid since the conduction through the particle is much larger than the convection on the surface. The equilibrium tube is 53 cm and it can safely be assumed that the particles investigated in this study are at flow conditions by the time they exit the equilibrium tube.

Figure 6: Particle Non-dimensional Temperature

Figure 7: Particle Non-dimensional Velocity

After the dust passes through the equilibrium tube, it enters the test fixture. A schematic of the test fixture is shown in Figure 8. The test fixture is made out of Hastelloy X, which is a common nickel-alloy used in the hot section of gas turbines. The test fixture is inserted in an electric kiln starting at the transition from circular tubing to a rectangular channel. It has a one dimensional expansion that also starts at this transition point that expands the flow to the height of the test article. The expansion angle is 2.4° which was chosen to prevent the flow from separating from the test fixture walls. Due to the length of the test fixture, it had to be assembled inside the kiln which required the use of a flange between the expansion and the rest of the fixture. Ceramic gasket is placed between the flanges to prevent air leaking at the flange joint.

Figure 8: Test Fixture Schematic

The fully expanded rectangular channel is 25.4 mm x 12.7 mm. Temperature and static pressure measurements are taken in this section. The temperature is measured with a 1.58 mm diameter sheathed thermocouple placed 77.1 mm upstream of the test article and 6 mm into the flow. Since the test fixture is in an electric kiln, there is radiation heat transfer occurring along the test fixture causing it to increase in temperature. To prevent this from having too significant of an effect on the flow temperature measurement, the test fixture is covered in insulation. Despite the insulation, the test fixture reaches temperatures up to 1080 K. Due to the thermocouple being exposed to the hot test fixture, the temperature reading must be corrected for radiation from the surrounding metal, convection from the coolant, and conduction along the sheath. This is done as described by West and Westwater [37]. First, an energy balance is performed on the inner surface of the test fixture. One dimensional conduction is assumed through the test fixture wall with the measured wall temperature on the hot side and a convection boundary condition on the cool side using a rectangular duct Nusselt number (Nu) correlation of 3.39. This is used to estimate the interior surface temperature of the test fixture. The thermocouple's bead is treated as a sphere and a Nu correlation is used to estimate the convective heat transfer across the thermocouple. Conduction along the sheath, convection from the flow,

and radiation from the walls are then used to estimate the gas temperature. An emissivity curve taken from Brundage et al. [38] for oxidized Inconel was digitized and a fourth order polynomial was used to reconstruct the curve for this calculation. Inconel is a nickel alloy similar to that used for the test fixture and it is assumed that the two materials have the same emissivity. The heat transfer analysis is iterated by using the estimated gas temperature for the coolant temperature until the gas temperature converges to within 0.5 K.

Static pressure is measured 46.5 mm upstream of the test article by an Omega 0-1 PSI differential pressure transducer exposed to ambient on one end (P_{diff}). The transducer has an accuracy of 0.08% BSL which corresponds to ± 2.4 Pa for a typical test with a P_{diff} of 3030 Pa. Once the flow passes over the test article, some mass flow will exit the effusion holes thus reducing the pressure and mass flow through subsequent holes. In order to keep the velocity and mass flow into each hole constant, the cross sectional area of the test fixture in the region of the test article was reduced. A schematic showing the measurement locations and reduction in test section area is seen in Figure 9. A computational fluid dynamic simulation of this geometry, detailed later in Chapter 3.2, shows that the mass flow through each hole is relatively consistent along the length of the plate.

Figure 9: Test Fixture Cross-Section

The electric kiln in this facility allows for independent control of the plate surface temperature and the coolant temperature. The external plate surface temperature was measured using a Cedip Silver Infrared Camera with an integration time of 75 μ s. A mirror between the kiln viewport and the camera was required to protect the camera from damage. The camera reported information in digital levels (DL), a measure of the received IR intensity. In order to get useful information from the digital levels, the camera was calibrated once every 20 tests during the heat up. The digital levels vary spatially along the plate's length and height. A single thermocouple would not be able to capture this information which is why this method is required.

To calibrate the IR camera, a thermocouple was welded to the edge of the plate away from any of the cooling holes. As the plate heated up, the DLs on the outer edge of the plate and the thermocouple reading were recorded. An example of a curve fit used in these experiments is detailed in Equation 4. A power law fit was determined as the best curve fit for the data shown in Figure 10. Using the standard error of fit, it was determined that the uncertainty of this measurement is ± 5 K.

Figure 10: Plate Calibration Curve

$$T = 53.86(DL)^{0.3804}$$

4

Applying this calibration to the IR output directly yields Figure 11 which shows the spatial variation in the plate temperature due to the film cooling. In order to determine a single value for the test condition, an area averaged temperature was calculated by drawing a box around the test area and finding an average DL. The average DL was then used to determine the average plate surface temperature.

Figure 11: Plate Temperature Distribution (K)

2.2: Test Article

Two flat plates of the same design were used to simulate the effusion cooling scheme of a modern combustor liner in these experiments. The plates were made of Hastelloy X sheet stock that was 1.27 mm thick. The test area consists of alternating columns of holes as shown below in Figure 12.

Figure 12: Test Article Schematic

There are 16 columns that contain 12 holes and 15 columns that contain 11 holes. The centerlines of adjacent columns are separated by 4.06 mm ($8 D_e$). Within each column, holes are spaced 2.03 mm ($4 D_e$) apart. The holes were manufactured through electrical discharge machining. Each hole is 0.5 mm in diameter and were cut at a 30° angle from the plate surface creating an L/D_e of 5. The plate is oriented on the test fixture such that the flow is parallel to plate flowing from left to right and must turn 150° to exit the effusion hole as shown in Figure 13.

Figure 13: Plate Orientation to Flow

A 3.18 mm ceramic gasket is placed between the test fixture and the test article in each test to prevent the particle laden coolant from leaking at the plate-fixture interface. The gasket is cut such that it fits around the border of the test area without obstructing any of the holes. Stiffening bars are placed on the exterior side of the test plate in order to prevent the plates from warping after consecutive testing. The entire assembly is bolted onto the test fixture with 11 4-40 screws.

2.3: Dust Characterization

The type and size of dust used in deposition experiments are important parameters to control. The dust used in this body of work is ARD, which is a common dust used in

these types of experiments [11, 13-16, 21]. Since the coolant in an engine is taken from the compressor, Dunn's findings that the mass mean particle diameter in the bleed of the high pressure compressor was 6 μm indicate that particles around this size should be focused on. Whitaker et al. [15] showed that in an impingement-film cooling geometry, different sized particles within the range of 0-20 μm can have opposite effects on deposition, with the smallest particles causing deposit growth and large particles causing erosion. For these reasons, six unique size distributions of ARD were used in the current experiments to investigate the role particle size has on deposition in an effusion cooling geometry. All of the sizes have the same chemical composition as reported by the manufacturer Powder Technologies Inc. [39] (PTI) and can be seen in Table 1.

Table 1: ARD Chemical Composition

Chemical	Percent by Weight
SiO ₂	68-76 %
Al ₂ O ₃	10-15 %
Fe ₂ O ₃	2-5 %
Na ₂ O	2-4 %
CaO	2-5 %
MgO	1-2 %
TiO ₂	0.5-1.0 %
K ₂ O	2-5 %

The six ranges looked at in these experiments are 0-3 μm , 0-5 μm , two different 0-10 μm ranges, 5-10 μm , and 10-20 μm . The two 0-10 μm dust distributions were different batches provided by the manufacturer when the dust was ordered. The size distributions of the six dusts can be seen in Figure 14 as reported by the manufacturer. It can be seen that there is a significant amount of mass below 3 μm in diameter for the 0-3

μm , 0-5 μm , and 0-10 (I) μm ranges. Despite being in the same range of particle sizes, 0-10 (I) and 0-10 (II) have very different size distributions. 0-10 (I) has 36% of its mass below 3 μm while 0-10 (II) has only 8% of its mass below 3 μm . The primary difference between these two distributions is below 5.5 μm . In Table 2 the mass median diameters as well as the cumulative mass fractions are shown over this range. The mass median diameters of 0-10 (I) and 0-10 (II) are 3.821 μm and 5.278 μm respectively.

Figure 14: Particle Size Distributions

Table 2: Dust Distributions' Characteristics

Size Range (μm)	Mass Median Diameter (μm)	Cumulative Mass Fraction by Diameter (μm)						
		2.5	3	3.5	4	4.5	5	5.5
0-3	1.14	93.6	95.1	96.1	97.0	97.7	98.3	98.3
0-5	2.088	67.3	82.9	92.5	97.0	98.9	99.7	100.0
0-10 (I)	3.821	27.0	36.0	44.6	52.9	60.5	67.6	73.7
0-10 (II)	5.278	2.9	8.4	15.3	23.8	33.4	44.0	54.9
5-10	6.433	0.3	0.4	0.7	1.5	4.0	10.4	22.1
10-20	13.21	0.0	0.0	0.0	0.0	0.0	0.04	0.07

2.4: Test Procedure

Prior to the beginning of a test, each dust type was dried in the kiln at 477 K (400° F) for 10 hours. The dust is allowed to cool and then is stored in airtight containers with small desiccant packs. These containers are kept at room temperature until dust is required for an experiment.

A typical test procedure requires six to seven hours to complete from set up to cool down and is conducted as follows. A test article is selected, cleaned of dust from a previous test, and weighed. To clean a plate, dust is first removed with shop air. Then it is cleaned in an ultrasonic cleaner using a dilute basic solution. The plate is removed and visually inspected for remaining dust. If dust remains in the holes, small pins are used to mechanically remove the dust and then cleaned in the ultrasonic cleaner again. This process is repeated until no dust remains in the holes. A gasket is then manufactured and the test article is assembled to the test fixture. A VI in LabVIEW is used to control the

mass flow rate based on the pressure ratio across the test article which is reported as backflow margin (BFM) in the relation below.

$$BFM = \frac{P_{diff}}{P_{amb}} * 100 \quad 5$$

The kiln is not air tight and thus is at ambient pressure. It follows then that the P_{diff} measurement records the change in pressure across the plate. A low Mach number (Ma) approximation can be made, allowing the static pressure measurement in the flow to represent the total pressure. Ambient pressure is measured and then ambient temperature air is provided to the test article without the kiln on. The mass flow rate and BFM are recorded and compared to previous tests. The direct comparison to previous tests is used to verify that no previous dust remains in the test article and that the system is sealing properly.

Once the system is determined to be leak free, the kiln is turned on and a constant mass flow rate is set to prevent the test fixture from becoming too hot. The kiln heats up over 3 hours from ambient to the desired temperature. During this time period, the dust is weighed and loaded onto the conveyor belt. To encourage consistent dust delivery, guide walls are put on the conveyor belt and the dust is loaded between them. Then a leveling tool is used to create a dust layer of constant thickness. The length of the dust on the belt is measured and used to calculate the motor speed that will deliver dust over a set period of time. The top to the dust delivery system is then clamped in place.

With the dust in place, the inline heater is ramped up to temperature and the IR camera is positioned. When the kiln reaches the set temperature, it has an initial control loop that sees a large decrease in temperature. It takes five to ten minutes for it to return

the desired temperature and then enters a control loop with a faster response time that keeps the kiln at a constant temperature. The initial long control loop occurs any time the setting of the kiln is changed. For this reason, the kiln setting is not changed during a test even if the plate temperature increases. After the proper coolant temperature, plate temperature, and BFM are measured, the test commences. The drop tube valve is opened, additional mass flow into the dust delivery system is provided, and the dust gets delivered to the test article. IR images are taken every five minutes during the test to monitor the plate temperature. When significant amounts of dust make it through the effusion holes, it can deposit on the external surface of the test article. The dust has a different emissivity than the metal and can skew the IR temperature measurement.

The motor speed is set so that the test duration is between 45 and 60 minutes. This creates low loading rates where the volume loading is the ratio of particle volume to the sum of the particle and the total flow volume as shown in Equation 6.

$$\phi = \frac{V_p}{V_p + V_f} \quad 6$$

There are three regimes where the effect of the suspended particles on turbulence can be seen. One-way coupling exists for only very dilute suspensions where the flow field is unaffected by the presence of the particles, but the flow directs the particles. Two-way coupling occurs with increased loading where the particles begin to change the flow field. Four-way coupling is a dense suspension where particles not only affect the flow field but also interact with each other. Figure 15 shows the regime boundaries described by Elghobashi [40]. In all the tests conducted, the volume loading was well within the one-way coupling regime.

Figure 15: Particle Interaction Regimes [40]

When dust begins to deposit within the effusion holes, the BFM, or pressure ratio, begins to increase. This behavior can be explained through the equation for a discharge coefficient (Equation 7).

$$C_d A = \frac{\dot{m}}{\sqrt{2\rho_f \Delta P}} \quad 7$$

As the dust builds up in the hole, it acts as an area constriction and likely lowers the C_d as well. Fluid density is constant during these tests so for a constant mass flow rate, the difference in pressure across the orifice needs to increase to compensate for the change in $C_d A$. The coolant provided in a combustor liner has a constant pressure condition not a constant mass flow rate condition. In order to reflect this reality and better model engine conditions, the mass flow rate is decreased during the test to keep BFM at a constant 3%. This is done through a simple control algorithm in the LabVIEW VI that is used to monitor and control a test as well as record all the data. An important parameter for these tests is the amount the mass flow has been reduced during the test as defined in Equation 8 as R or mass flow reduction.

$$R = \left(1 - \frac{\dot{m}_c}{\dot{m}_{int}}\right) * 100 \quad 8$$

The initial mass flow rate is recorded at the beginning of the test before any dust has been delivered and the cooling holes are clean. The current mass flow rate is a measured value output by the mass flow controller. As defined above, R is a non-dimensional representation of the mass flow reduction which quantifies the level the dust blocks the hole. When R is zero, the hole is clean and unimpeded by dust deposits. When R is at 25, the mass flow rate has been reduced by 25% and the holes are considered 25% blocked. The test concludes when either the R reaches 25 or 0.75 grams of dust are injected into the system. If there is any dust remaining on the conveyor belt, it is collected and weighed. This allows for an accurate account of the mass of dust injected.

With the test concluded, the kiln is turned off and the inline heater is ramped down. The mass flow rate is set to the last value of the test while the hot systems cool down. This prevents the inline heater from burning out and the test fixture from becoming too hot. The mass flow is turned off after the inline heater and kiln reach safe levels. The entire system is then allowed to cool overnight.

2.5: Post Test Procedure

After the facility is cool, the test article is removed from the test fixture and weighed. Pictures are taken of the plate after the test to show the deposit shapes. An example of this is seen in Figure 16. The first things to look for are dark tan lines leading towards the edge of the plate. These indicate leak paths that the dust follows and deposits

outside the test area. No leak paths are seen in this picture. The second item of note is the relative uniformity of the deposit structures. At the leading edge of the plate, the flow must navigate a backward facing step the thickness of the test fixture wall and gasket. This creates a shadow region over the first four rows of holes where the flow recirculates. Particles in this region create differently shaped structures than those seen along the plate due to flow differences. At the trailing side of the plate, the structures begin to look less uniform. This could be due to natural particle filtering. Small particles are more likely to follow flow streamlines than large particles and thus are more likely to enter the holes. This means by the time the flow reaches the trailing side of the plate, the particle size distribution may be skewed to larger particles.

Figure 16: Post-Test Plate

The structures create interesting shapes and are examined more closely using a microscope with a digital camera attachment. All the structures reported in this body of work are from the 15th column from the leading edge and the 6th hole up from the bottom of the plate and is circled in red in the figure above. This places the structure of interest

near the very middle of the plate where the particle size distribution is less affected by any natural filtering that may occur and avoids any edge effects.

2.6: Test Matrix

The test matrix for this study is shown below in Table 3. For the first test campaign, each dust size distribution, aside from 10-20 μm , was investigated independently. This allows for direct comparison between the different size distributions in order to determine which particles may be causing blockage. These first tests are labeled as “x” in the test matrix. The second test campaign look at sequentially loading different size distributions and are labeled as “o” in the test matrix. The primary or first dust loaded in all these tests is the 0-10 (II) distribution. Then a mass equivalent to the 0-10 (II) of either 5-10 or 10-20 is injected. Since these are the largest two distributions, these tests parse out the possible effects that the large particles are having. These are seen in the test matrix as “o” markers. Each test was repeated twice to demonstrate the results were repeatable.

Table 3: Test Matrix

Dust Size (μm)	Arizona Road Dust Size Distributions					
	0-3	0-5	0-10 (I)	0-10 (II)	5-10	10-20
Primary Dust	x	x	x	x, o	x	
Secondary Dust					o	o

Chapter 3. Numerical Methods

3.1: Domain and Solvers

Due to the size of the dust and physical limitations of the facility, it was infeasible to capture particle impact locations as a function of time during experimentation. One way of visualizing where particles impact and stick is to track particles through a converged CFD solution. Companion CFD studies were conducted for this reason on three fluid domains. Ideally, the entire plate and test fixture would be modeled but this would result in an excessively large grid that would be costly in terms of computational resources. To reduce grid size, a small subsection of the cooling array is desired. Since the experimentally measured pressure is upstream of any of the holes, a thin section of the entire test section and plate was modeled in order to determine the appropriate inlet conditions for a smaller domain. The thin section in relation to the test plate can be seen in Figure 17.

The domain cuts through the mid-plane of two adjacent rows of holes resulting in a total of 31 half holes modeled. Symmetry boundary conditions are applied to these planes. The other boundaries are set up to reflect the experiment. A stagnation inlet is set using the experimentally measured upstream pressure and temperature. The solid portion of the plate is not modeled in these simulations aside from the surfaces that interface with the fluid domain. The plate surfaces are set as constant temperature no-slip walls. The

exterior surface temperature of the plate is measured experimentally with an IR camera. The target surface temperature from the experiments is used as the plate surface temperature in the simulations. A thin plate assumption is used to set the interior side of the plate at the same temperature. The walls of the test fixture are insulated during the experiment and are considered adiabatic in the simulation. A static pressure outlet at ambient pressure and the kiln gas temperature is used to simulate the conditions that the holes exhaust to in the kiln. A schematic of where the boundary conditions are applied is shown in Figure 18 and all the boundary values tabulated in Table 4.

Figure 17: 31 Half-Hole Domain

Figure 18: Half-Hole Domain Boundary Condition Diagram

Table 4: Domain Boundary Conditions

Boundary	Type	Pressure (atm)	Temperature (K)
Flow Inlet (1)	Stagnation Inlet	1.03	950
Jet Outlet (2)	Pressure	1	1230
Plate/Hole surfaces (3)	Constant Temperature	----	1118
Test Fixture (4)	Adiabatic	----	----
Hole Mid-Plane	Symmetry Plane		

The flow was solved as a three dimensional simulation using the commercial finite volume solver Star CCM+. A steady second order implicit coupled RANS solver was used to get a converged solution. The fluid medium is air modeled as an ideal gas with dynamic viscosity and thermal conductivity based on Sutherland's Law and a specific heat fit to a polynomial according to temperature. The $k-\omega$ SST model with an inlet turbulence level of 1% was used. This model was chosen based on similar simulations that used the $k-\omega$ SST model [13, 16, 21, 23, 34]. The fluid geometry was meshed in Star CCM+ using an unstructured advancing layer mesher with 5 prism layers

to capture the near wall region and a max wall y^+ less than 1.09. The mesh can be seen in Figure 19.

Figure 19: 31 Half-Hole Mesh

After a converged solution was found for the 31 half-hole domain, two additional domains looking at the 15th and 16th holes were investigated. The first domain represented the cooling holes prior to dust injection (clean holes) and is considered a baseline case for initial deposition. The domain extends from the surface of the test fixture through the plate and terminates $8.6 D_e$ after the hole outlet. The domain can be broken up into three sections: the primary flow, the holes, and the jet region. The primary flow region extends from the test fixture surface to the plate surface encapsulating the flow through the test fixture. The flow near the plate turns into the holes which exhaust into the jet region. This subsection of the cooling array can be seen in Figure 20 with the flow direction is from left to right in the through the primary flow region.

Figure 20: Clean Hole Domain

The boundary conditions in the clean hole domain are the same as the half hole domain for the test fixture, plate, and jet outlet boundaries. A one-dimensional pressure profile was taken from the half-hole domain and used as pressure inlet for this domain. The primary flow outlet pressure was varied until the inlet and hole mass flows matched the values found in the half-hole simulation. This domain is in the middle of the cooling array. To simulate the adjacent cooling holes, periodic translational boundary conditions were used on the sides of the primary flow and jet regions as well as the fore and aft boundaries of the jet region only. This allows the flow features on a translational boundary to be transposed onto the matching boundary thereby simulating adjacent cooling holes.

Structures were added to the clean hole domain to represent the structures seen with 25% blockage caused by dust 0-10 (II). The structures are curved conical shapes that extend $1 D_e$ above the plate surface and are $2.6 D_e$ long. These dimensions were chosen based off of measurements taken from the deposits seen in the experiment. A portion of

the structure extends into the hole to simulate the tongue portion of the deposit. The tongue smoothly transitions into the curved front surface. The curvature of the front surface and the tongue were estimated based on pictures of the deposit after it was poked out of the hole. Figure 21 shows a comparison of the simulated structure and the experimentally created structure. Adding these structures allows one to see the effect that the dust deposit has on the flow and particle trajectories.

Figure 21: Comparison of Experiment Deposit and Simulated Deposit

The deposit structures likely have different material properties than the homogenous metal surface but the material properties of dust agglomerations are difficult to measure or find in the open literature. Since these properties couldn't be found, the

structures use the same boundary conditions and material properties as the plate surfaces in the simulations.

The mesh was refined $2 D_e$ above and $1 D_e$ below the plate surface for both the clean hole and scoop domain. This allowed for adequate resolution in the holes without requiring unnecessary refinement in the other areas of the domain. The flow was solved using the same scheme as the half hole domain. The max wall y^+ is approximately 1 in all the simulations. Examples of the mesh of the clean hole and scooped hole domain taken at the mid-plane of the first hole can be seen in Figure 22 and Figure 23.

Figure 22: Mesh of a) clean hole, b) scooped hole

Figure 23: Mesh near the inlet of the a) clean hole, b) scooped hole

3.2: Mesh Independence Study and Validation

An important aspect of any computational study is determining the dependency that the solution has on the mesh itself. A mesh independence study was conducted on all the domains. A solution was considered converged when the absolute residuals stopped changing and reached an appropriate level. The convergence criteria are detailed in Table 5. An initial solution was found for each of the domains with the cell sizes determined by an initial base size. Then the base size was decreased by 20% which resulted in a doubling of the number of cells for the two hole domains and a 46% increase in cell count in the half hole domain. The simulations were run again using the same boundary conditions on the refined mesh. The mass flow rate at the inlet, the mass flow through the holes, and the average velocity at the hole outlets were then compared between the different sized meshes. The results of these studies are shown in Table 6.

Table 5: Absolute Residual Convergence Criteria

	Continuity	X,Y,Z Momentum	Energy
Convergence Level	10^{-9}	10^{-9}	10^{-5}

Note that the inlet mass flow rate for the half hole domain is taken at the same physical location as the inlet to the clean hole domain. Additionally, the mass flow rates reported in the half hole domain are multiplied by two to account for this domain having half the flow area as the clean hole domain. This allows for a direct comparison between the two domains. The important flow characteristics outlined above change by less than 0.42% when the cell count is increased by 46% in the half hole domain. This means that the flow solutions do not have a strong dependency on the mesh. Moving forward, any comparisons made against the half hole domain will refer to the solution found on the first mesh.

Table 6: Mesh Independence Data

Geometry	Half Hole Domain		Clean Hole Domain		Scoop Hole Domain	
	Mesh 1	Mesh 2	Mesh 1	Mesh 2	Mesh 1	Mesh 2
Cell Count	979522	1430323	324141	744062	312855	760788
Inlet Mass Flow Rate (kg/s)	7.09E-05	7.11E-05	7.02E-05	7.01E-05	6.89E-05	6.86E-05
Hole 15 Mass Flow Rate (kg/s)	4.10E-06	4.10E-06	4.17E-06	4.13E-06	3.48E-06	3.44E-06
Hole 16 Mass Flow Rate (kg/s)	4.10E-06	4.11E-06	4.17E-06	4.13E-06	3.44E-06	3.42E-06
Hole 15 Mass Average Velocity (m/s)	77.48	77.29	77.76	76.61	66.07	64.88
Hole 16 Mass Average Velocity (m/s)	77.51	77.47	78.33	77.27	66.12	64.69
Inlet Mass Flow % change	0.42		0.18		0.49	
Hole 15 Mass Flow % change	0.11		0.96		1.11	
Hole 16 Mass Flow % change	0.32		1.00		0.72	
Hole 15 Mass Average Velocity % change	0.25		1.48		1.80	
Hole 16 Mass Average Velocity % change	0.06		1.35		2.17	

For the clean hole domain, it can be seen that by doubling the cell count, the inlet mass flow, mass flow through the holes, and average hole exit velocity changes by less than 1.8 %. Comparing this solution to the half hole solution it can be seen that the mass flow rates match within 2% of each other. This gives confidence that the clean hole and

half hole solutions converge to a similar solution. Similarly, roughly doubling the cell count in the scoop hole domain generated less than 1.80 % change in the inlet mass flow, hole mass flow, and average hole exit velocity. Both of these results show that the solutions have a small dependency on mesh size which is likely not significant in tracking particles and so the first meshes were used.

One method of validating the numerical solution flow is to compare it to values found in the experiment. The mass flow rate in the experiment is the aggregate mass flow through the entire system. In order to compare the experiment and numerical solutions, it was assumed that each hole in the experiment exhausts the same amount of mass. Multiplying the assumed hole mass flow rate by the number of holes upstream of the clean hole inlet gives the mass flow lost prior to the domain. Subtracting this from the experimentally measured mass flow rate gives an estimate of the mass flow rate at the plane of the domain inlet. Since the domain is only a small section, multiplying the inlet plane mass flow rate by the ratio of the domain inlet area to the test fixture cross sectional area gives an estimated mass flow rate into the numerical domain. This is detailed in Equations 9 and 10.

$$\dot{m}_{hole} = \frac{\dot{m}_{experiment}}{N_{total\ holes}} \quad 9$$

$$\dot{m}_{inlet} = (\dot{m}_{experiment} - N_{upstream\ holes} * \dot{m}_{hole}) * \frac{A_{domain}}{A_{test\ fixture}} \quad 10$$

The comparison between the experiment and clean hole domain can be seen in Table 7. The numerical mass flow rate deviated from the estimated experimental mass

flow by 16% and 22% for the inlet and through both holes respectively. Comparing the area average velocity through the holes shows the same 22% deviation from the assumed experimental value as is seen in the hole mass flow rate. The difference in mass flow rates requires an investigation to find a possible explanation.

Table 7: Comparison of Experimental and Numerical Flow Data

	Domain Inlet Mass flow Rate (kg/s)	Mass flow of both holes (kg/s)	Average Hole Exit Velocity (m/s)
Experiment	8.40E-05	10.7E-06	73.5
Simulation	7.02E-05	8.34E-06	57.1
% difference	-16.38	-22.24	-22.24

It was assumed that the flow through all the holes is identical. Figure 24 shows a plot of the mass flow through each hole for the 31 hole domain, the clean 2 hole domain, and the estimated experimental value. The mass flow along the plate varies from the mean with a standard deviation of 1.6% of the mean value. There is more mass flow though the first three columns of holes. Recalculating the estimated experimental mass flow using the same mass flow rate distribution of the half hole domain reduced the inlet mass flow by less than 0.40%. This indicates that the assumption that each hole has the same mass flow is a valid assumption.

Figure 24: Mass Flow of Each Hole

Another assumption made is that the hole is exactly 0.50 mm. The holes of the test article were measured using no-go pin gages with a resolution of 0.025 mm between gage sizes. The nominal value of 0.50 mm for the hole diameter was chosen based on the largest gage that could successfully pass through the holes. If the holes are larger in reality than in the simulation, the experimental mass flow through the holes would be greater than predicted in CFD. Another assumption made was that the static pressure measured in the experiment is equal to the flow total pressure due to it having a low Ma. In order to determine if these could be a possible explanation, the half hole domain was revised twice. The hole diameters were increased to 0.51mm and 0.52 mm and the stagnation inlet pressure was increased to the isentropic stagnation pressure of the measured flow.

Table 8: Half Hole Domain Changes

Inlet Total Pressure (atm)	1.03	1.0305	1.0305
Hole size (mm)	0.5	0.51	0.52
Area (mm ²)	0.196	0.204	0.212
% increase in Area	N/A	4.04	8.16
C_d (Lichtarowicz)	0.603	0.6096	0.6149
% increase in C_d	N/A	1.0979	1.9815
% increase in $C_d A$	N/A	5.18	10.3
Mean hole mass flow	2.057E-06	2.188E-06	2.334E-06
Mass flow STD Dev	3.470E-08	3.887E-08	1.253E-08
% change in mean hole mass flow	N/A	6.4	13.46
% difference from experiment	-23.28	-18.37	-12.95

It can be seen in Table 8 that increasing the hole size and total pressure increased the mass flow through the holes by 5.6% and 11.5% respectively. For long orifices such as this, it is known that the discharge coefficient is a function of Re for low Re [41]. It can be seen that the predicted change in $C_d A$ closely matches the change in mean hole mass flow. This means that the change in hole size was primarily responsible for the increase in mass flow and that the change in total pressure did not contribute significantly. These results also indicate that the hole diameters in the experiment were likely larger than the 0.50 mm holes used in the simulations. Since the exact size is unknown, the measured 0.50 mm diameter will be used for the particle injection simulations. Other contributing factors that could affect the C_d experimentally are the development of boundary layers on the test fixture walls and the difference in flow near the edges. For the same mass flow, the presence of boundary layers means that the core flow velocity will increase and thus increase the Re . This would increase the C_d and result in a higher mass flow through the

holes. Since the half hole simulation takes a slice down the center of the test fixture, these boundary layers are not accounted for. This change in C_d due to a higher Re could also be a contributing factor in the discrepancy seen. Similarly, the holes around the perimeter of the plate will not see the same flow as center rows since there are not adjacent cooling holes. An inclination angle of 150° creates pressure loss resulting in a low C_d . If the flow enters at different angle, the C_d could improve resulting in more mass flow exhausting through these holes. This would also encourage more mass flow experimentally than is simulated.

Another way to investigate the flow is to compare it to other numerical film-cooling studies. Figure 25 shows a comparison of a study done by Kampe [23] and the flow velocity found in this study. The L/D_e , flow conditions, and inclination angle are different between the two studies so a direct comparison of velocities can't be made. What can be seen though is that for the shorter L/D_e case, similar flow characteristics are observed. A separation bubble develops on the sharp expansion corner and accelerates the flow on the leeward side of the hole. The flow then jets out of the hole and does not reattach to the plate. Although the difference between the hole mass flows found experimentally and numerically is not ideal, this comparison provides further confidence in the viability of the numerical solution as a tool for gaining insight on particle trajectories. It shows that the flow field that will influence particle trajectories is being set up as expected.

Figure 25: Film Cooling Solution from a) Kampe [23], b) Two Hole Domain

3.3: Particle Injection and Tracking

Particles were injected and tracked through the converged solution using a Lagrangian Multi-Phase model that is built into Star CCM+. This model calculates the forces acting on the particle from the flow field (pressure gradients, drag, and shear lift) assuming the particles are spherical. Balancing these forces with the particles' inertia allows for a determination of the particles' trajectories through the flow. Since small particles will be more likely to follow the flow out of initial holes, the particle size distribution at the middle of the plate is unknown. In order to make a direct comparison

of impact and sticking frequency, a flat distribution of 56,000 particles was injected in 28 discrete size bins over the range of 0.5 to 20 μm (2,000 particles of each size). These particles were chosen so as to visualize where each particle size would be likely to impact. This does not represent any specific particle size distribution tested experimentally. The mass of the particulate is much smaller than the mass of the air that passes through the simulation. This placed the loading within the one-way coupling regime and the solver was set up to reflect this.

Each particle was placed at a random location in the inlet and released at a velocity of 7 m/s with a temperature of 950 K. It was seen that any particles above 4 D_e would exit the primary outlet without interacting with the effusion holes. To conserve time and computational resources, particles were injected within 4 D_e so as to only simulate particles that interact with the cooling hole. A random walk technique was used to simulate turbulent dispersion. This results in unique particle trajectories regardless of initial injection location.

The particle Stokes number (Stk_p), defined in Equation 11, is the ratio of a particle's characteristic time to a characteristic time of the fluid flow. Particles with a Stk_p much less than one are likely to follow the flow streamlines. When the Stk_p exceeds unity, particles act ballistically. The difference in flow velocity at the inlet of the domain changes the Stk_p as can be seen in Figure 26. This shows that for particles with a low Stk_p , the 20% difference in velocity does not dramatically change the Stk_p . This means that the particles will behave in a similar manner in the numerical simulation as one would expect them to act experimentally. Thus tracking particles through the domain will

provide insight into where the particles are hitting experimentally despite having a different flow field.

$$Stk_p = \frac{\rho_p * D^2 * U_0}{18 * \mu_f l_d}$$

11

Figure 26: Stokes Number of Particles

The OSU deposition model developed by Bons et al. [31] was used to determine particle impact behavior with material property updates suggested in the literature. The model calculates the energy lost due to elastic-plastic deformation during impact assuming a cylindrical shape. If the remaining energy was enough to overcome the work of adhesion, the model calculated a CoR. The calculated CoR is then sent to the Lagrangian solver to determine the rebound trajectory. If the model determined a particle

stuck, then the particle was removed from the simulation and the sticking location was recorded. The CoR calculation is intrinsically dependent the particle material properties. Material properties for small dust are difficult to find and determining appropriate values is an active area of research. Whitaker [33] proposed a velocity dependent yield strength for ARD. The properties from his work are compared to constant properties and are shown in Table 9. As impact velocity decreases to zero, the variable yield strength also decreases to zero. This does not make physical sense since a particle will have a yield strength regardless of strain rate. To address this, a lower limit of 100 MPa is applied to the variable yield strength formulation to ensure realistic material properties. This value was chosen based on the lower limit of mean yield strength seen in Whitaker's data [33].

Table 9: Particle Material Properties

	ARD Properties				
Density [kg/m ³]	Effective Young's Modulus (E_{eff}) [GPa]	Surface Free Energy (γ) [J/m ²]	Variable Yield Strength (σ_y) [MPa]	Constant Yield Strength (σ_y) [MPa]	Impulse Ratio
2727	72.3	0.8	$3.59 \cdot V_{impact}$	145	0.68

Chapter 4. Experimental Results

4.1: Single Dust Tests

4.1.1: Test Conditions and Preliminary Data

The goal of this body of work is to ascertain the relationship between the size of particulate and its propensity to stick to an effusion cooling geometry. Internal deposition is known to be sensitive to metal temperature, coolant temperature, total particulate mass, pressure ratio, geometry, and total pressure. In order to determine the effects of particle size distribution, all of these variables need to be controlled for. In all of the tests conducted the BFM, operating pressure, test plate average temperature, and coolant temperature were all held constant and are shown in Table 10. There were two of the described plates used in these tests that were reused and cleaned between tests. This effectively controls for the effects that geometry may have. In the case of operating pressure, the ambient pressure in the lab was recorded prior to each test using a mercury barometer. It was seen to vary less than ± 670 Pa over the entire test series. There was some variation in the temperatures from test to test. The average plate temperature is a function of the kiln setting, coolant temperature, and coolant mass flow rate. As a result, the initial average plate temperature varied ± 10 K over the entire test series. The coolant temperature was directly controlled by the level of preheating done by the inline heater and thus it only varied by ± 2 K over the test series.

Table 10: Test Conditions

Variable	Value	Uncertainty	Units
BFM	3%	0.003%	-
Initial Average Plate Temperature	1108 - 1128	5	K
Coolant Temperature	948 - 952	5	K
Exhaust Pressure	97870 - 99210	2.4	Pa

As previously discussed, the kiln setting is not changed during a test due to a long control lag time. This results in the average plate temperature increasing by no more than 15 K during a test as mass flow decreases.

The primary method of quantifying particulate deposition is by investigating the reduction in mass flow as particulate is introduced to the system. Each test required a different amount of dust to achieve a mass flow reduction (R) of 25%. Figure 27-Figure 31 show the reduction and BFM history plots for each of the dusts investigated. These figures are characterized by spikes in BFM and a stepwise increase in reduction. The test dusts used tend to fall into the funnel in discrete clumps. This results in periods without dust getting injected followed by a short period of high dust concentration. When dust deposits in the holes, the pressure increases which shows up as a spike in BFM when a discrete packet of dust gets injected. Then the control algorithm acts and reduces the mass flow which increases R. The control algorithm only changes the mass flow after a BFM threshold is reached. This creates the stepwise behavior of R.

Figure 27: History of a) R and b) BFM for 0-3 μm Dust Distribution

Figure 28: History of a) R and b) BFM for 0-5 μm Dust Distribution

Figure 29: History of a) R and b) BFM for 0-10 (I) μm Dust Distribution

Figure 30: History of a) R and b) BFM for 0-10 (II) μm Dust Distribution

Figure 31: History of a) R and b) BFM for 5-10 μm Dust Distribution

In each of the reduction histories, there is a time at the beginning of the test where blockage doesn't occur. There are two explanations for this behavior to exist. The first is that the data for these plots starts recording as soon as the conveyor belt motor is turned on. Prior to starting the test, the conveyor belt is turned on to get the dust as close to dropping into the funnel as possible. Despite this, there exists a time at the beginning of the tests where the conveyor belt is moving but dust does not drop into the funnel. This distance changes from test to test and can account for some of the delay in blockage. The second reason can be explained as dust getting trapped in fittings leading to the test article. There are four fittings between the funnel and the test article. These fittings will have recirculation zones due to sudden changes in path diameter. Some of the dust can get trapped in these zones and the fittings themselves. After each test, air is blown

through the facility to remove any residual dust that may be stuck in these fittings. Since this cleaning always happens, the fittings will trap dust at the beginning of each test.

In most of the tests, the plates block in a linear fashion. This behavior has also been seen in other facilities that follow a similar dust injection procedure using ARD in similar size ranges [14-16, 21]. The 0-5 tests and one of the test of the 0-10 (I) appear to exhibit non-linear blockage behavior. This can be explained as non-uniform dust injection. The mass flow and dust measurement information from each test can be seen in Table 11. Here a large difference between the mass of dust loaded and mass injected for the tests that appear to have non-linear blockage. The mass loaded is the mass of dust that is placed on the conveyor belt at the beginning of the test. Having significantly more dust loaded than injected means that only a fraction of the dust was injected before the test was stopped due to reaching the requisite blockage stopping criteria. The dusts with small particles have the tendency to stick to themselves instead of dispersing into separate particles like sand. As a result, in the tests with high mass loaded but low mass injected, the dust was delivered in more discrete packets than a fine continuous dusting. This can be seen in the BFM plots. When a packet of dust gets delivered, it creates blockage and a spike in BFM is seen. Then to compensate for this, the mass flow reduces significantly to return BFM to 3%.

Table 11: Test Mass Flow and Dust Mass Data

Dust Type	Test Number	Initial Mass Flow (kg/s)	Final Mass Flow (kg/s)	R	Mass Loaded (g)	Mass Injected (g)	Duration (minutes)
0-3	1	0.00192	0.00141	26.9	0.2139	0.0668	25
	2	0.00198	0.00142	24.3	0.201	0.0575	20
0-5	1	0.00191	0.00136	28.6	0.7629	0.0852	10
	2	0.00199	0.00142	28.9	0.3073	0.0807	15
0-10 (I)	1	0.00189	0.00133	29.0	1.5	0.1625	10
	2	0.00190	0.00141	26.1	0.3415	0.1467	30
0-10 (II)	1	0.00192	0.00144	25.0	0.98	0.72	30
	2	0.00198	0.00148	25.2	1	0.72	86
5-10	1	0.00191	0.00189	1.4	0.73	0.73	70
	2	0.00190	0.00186	2.1	0.7393	0.7393	60

When packets are injected, they can also get stuck on the side of the funnel wall before being delivered. As more dust gets injected, the dust on the funnel wall will fall into the drop tube. This compounds with the clumping phenomena to create a non-uniform dust injection rate despite the conveyor moving at a constant rate. This is seen in Figure 28 and Figure 29 as significantly large spikes in BFM and consequently relatively larger rises in reduction. This creates the appearance of a non-linear blockage rate but in fact is an artifact of inconsistent loading.

Total blockage in internal cooling passages is known to be proportional to total mass of particulate injected [15]. Since each test reached a different R with a different amount of dust, the best way to directly compare tests is by normalizing the R by the amount of dust injected. This creates a new parameter called blockage percent per gram (BPG) defined in Equation 12. The uncertainty of BPG is determined using the partial

derivative method. Since the amount of dust varies over a large range, the uncertainty of BPG necessarily changes. BPG for each test and its associated uncertainty are tabulated in Table 12 and plotted in Figure 32.

$$BPG = \frac{R}{m_{inj}} \quad 12$$

Table 12: Test BPG Data

Dust Type	Test Number	R	Mass Injected (g)	BPG	BPG Uncertainty
0-3	1	26.9	0.0668	402.0	60.2
	2	24.3	0.0575	422.0	73.5
0-5	1	28.6	0.0852	335.9	39.5
	2	28.9	0.0807	358.0	44.5
0-10 (I)	1	29.0	0.1625	178.5	11.2
	2	26.1	0.1467	178.1	12.2
0-10 (II)	1	25.0	0.72	34.7	0.5
	2	25.2	0.72	35.0	0.5
5-10	1	1.4	0.73	1.9	0.2
	2	2.1	0.7393	2.9	0.2

Figure 32: Blockage Percent per Gram for Each Distribution

One way of understanding this plot is to recognize that a BPG of 100 corresponds with a theoretical test that blocks completely with exactly 1 gram of dust. From here, it makes sense that any test with a BPG greater than 100 would require less than 1 gram of dust to theoretically block completely. A BPG less than 100 then indicates that more than 1 gram of dust would be required to fully block a hole. The first observation is that the different dust types repeat well with respect to each other. This means that the blockage level is primarily dependent on the mass of the dust despite having non-uniform loading.

The second observation to be made is that the size distributions with smaller dust have higher BPG. This shows that particle size has a first order effect on deposition in an effusion cooling geometry. Looking back at particle size distributions in Figure 14, it can

be seen that the 0-3 and 0-5 size distributions contain a similar size range dust but different distributions. These dusts act more similar to each other than the larger dusts. This indicates that particles in this range may be the primary cause of hole blockage. As one may expect the 0-10 (I) distribution, which has a mass median diameter close to the average of the mass median diameter of the 0-5 and 5-10 distributions, has a BPG value about half way in between the 0-5 and 5-10 size distributions. Interestingly, 0-10 (II) does not behave in this manner. It has a BPG, and a mass median diameter, much closer to the 5-10 distribution than the 0-5 distribution. This change in mass median diameter has a dramatic effect on the blockage characteristic of the dust. Despite consisting of the same range of particles, the 0-10 distributions show very different blockage behavior. These data provide a qualitative look at how particle size effects diameter but makes one wonder which particles are primarily responsible for causing blockage.

4.1.2: Data Processing and Analysis

To better understand which particles are blocking the hole, it is useful to conduct a thought experiment and see how the data changes. Suppose that all particles of the same size have the same deposition behavior such that they all stick or they all rebound. This would separate the particles by size based on which particles stick. Above some critical diameter, the particles would stop sticking and only rebound off the plate surface without having an effect on blockage. If BPG then is calculated using the cumulative mass up to the critical diameter, it would show how well the thought experiment aligns with reality. If the thought experiment is correct, then one would expect to see all the dust size distributions have the same adjusted BPG (BPG_A). A similar method was employed by

Whitaker et al. [15] in their investigation of the effects of particle size on deposition in a leading edge simulator.

Adjusting BPG in this manner can be done according to Equation 13. By multiplying the mass injected in a test by the mass fraction (ω_d) below a specific diameter, only the dust below that diameter is accounted for in the calculation.

$$BPG_A = \frac{R}{m_{inj} * \omega_d} \quad 13$$

The results of this adjustment for seven different diameters can be seen in Table 13. For the sake of easy visual comparison, Figure 33 plots the data changes for different diameters when BPG_A is calculated. Data of constant color represent the particle diameter analyzed. The average BPG_A for each dust size distribution is plotted against the cumulative mass fraction of the analyzed diameter contained within that distribution. The dashed lines show how the data of one dust distribution changes based on which particle diameter is chosen. From this, it can be seen that BPG_A increases for all distributions as smaller critical diameters are analyzed. This makes sense since the cumulative mass fraction decreases with decreasing diameter so the R value is being divided by a smaller number. It can be seen that BPG_A flattens out at a critical diameter of 3 μm . This indicates that particles below 3 μm in diameter are the particles primarily responsible for blocking the cooling holes.

Table 13: BPG Adjustment Data

Diameter (μm)	0-3		0-5		0-10 (I)		0-10 (II)		5-10	
	w_d	BPG_A	w_d	BPG_A	w_d	BPG_A	w_d	BPG_A	w_d	BPG_A
2.5	93.6	436	67.3	516	27.0	761	2.9	1184	0.3	907
3	95.1	429	82.9	419	36.0	571	8.4	416	0.4	575
3.5	96.1	425	92.5	376	44.6	460	15.3	228	0.7	345
4	97.0	421	97.0	358	52.9	388	23.8	147	1.5	163
4.5	97.7	418	98.9	351	60.5	339	33.4	104	4.0	60
5	98.3	415	99.7	348	67.6	304	44.0	79	10.4	23
5.5	98.3	415	100.0	347	73.7	279	54.9	64	22.1	11

Figure 33: BPG_A vs Mass Fraction below a Certain Diameter

Replotting BPG against cumulative mass fraction below 3 μm in diameter gives a better quantitative assessment of the relationship between particle size and blockage. In Figure 34, it can be seen that BPG shows a strong monotonic trend with mass fraction of the dust below 3 μm in diameter. The same observations made from Figure 32 still hold true when the data is replotted in this way. The 0-10 (I) distribution has a BPG nearly the mean of the 0-5 and 5-10 distributions with a mass fraction slightly lower than half that of the 0-5 distribution. The 0-10 (II) distribution has a BPG and ω_d that is one tenth of the 0-5 distribution.

Figure 34: BPG vs Mass Fraction below 3 μm

This is useful information for comparing test conditions to conditions seen in the field and other experiments. Ideally, an accelerated deposition experiment will match conditions as closely as possible to the operating conditions of a gas turbine. This way the

physics investigated experimentally are the same physics governing the operation of actual hardware. These results suggest that the mass fraction of dust below 3 μm is an important parameter to match when using ARD to replicate mineral dust deposition seen on engine hardware. This doesn't speak to where or why the particles are sticking in the holes. To answer where the dust deposits, one can look at the structures that grow in the cooling holes.

4.1.3: Deposit Structure Discussion

When the dust deposits in the cooling holes, the particles build up into large structures that can be seen with the naked eye. The majority of the holes have similarly shaped structures that grow out of the inlet of the cooling hole. Figure 16 shows an example of these structures and how difficult it is to make an assessment of the shape and size of the structures. To better investigate the shape and size of the structures, images of the inlet deposit were taken from a top view using a microscope with a digital camera attachment. Figure 35 shows representative structures that were seen after the tests concluded. All of the images shown were taken under a 5x objective and are at the same position along the plate. The edges of the hole inlets have been outlined in red. The outline becomes a dashed line where the deposit obscures the hole edge. The particle laden bulk flow moves from left to right in the images and turns 150° into the hole.

Figure 35: 5x Magnification of Inlet Deposits using a) 0-3 μm , b) 0-5 μm , c) 0-10 (I) μm , d) 0-10 (II) μm , and e) 5-10 μm dust

These are images of three dimensional structures with the top of the deposit in focus. Due to the finite depth of focus, any part of the image that is out of focus is not planar of the deposit's top surface. This means that the blurred areas to the left of the deposits that are within the outlined edge is out of plane. Since this is looking at the deposit from the top view, this blurry area is the part of the hole that is below the plate surface or extends into the page plane. The dust shows up as a light tan or brown color which changes from image to image due to the settings on the camera. To the eye, all the deposits had a similar color. The plate and surfaces of the hole show up as dark blue or black.

The two smallest distributions, Figure 35 a) and b), create thin wedge shapes that extend from the leeward edge of the hole into the flow path and form straight up from the bottom edge of the hole. A coating of dust forms on the bottom surface but the extent and shape of this coating can't be seen from a top view. The 0-10 (I) dust, Figure 35 c), also creates a wedge shape but is much broader than the two smaller distributions and fills in more of the leeward side of the hole inlet. It also extends straight into the page until reaching the hole's bottom surface where a coating of dust forms. The 5-10 distribution only accumulated in the leeward side of the hole inlet and created a structure with a slightly concave front surface. This structure didn't extend far into the flow path of the effusion hole and thus didn't create much blockage as seen by the reduction history plots.

The structures that form from the 0-10 (II) dust are drastically different from the other structures seen. These structures were approximately one D_e tall, two D_e at the widest point, and 2.5 D_e from front edge to back edge. The dust adheres well enough to

itself that the structures could be manually removed from the hole with a pin gage. Figure 36 shows what these structures look like when poked out onto a slide. These structures have three distinct features. The first is a tongue which is in focus in Figure 36 (a) and out of focus in Figure 36 (b). This tongue extends into the hole from the plane of the plate's surface. The second feature is the leading face of the structure. This front face is slightly concave and extends from the leeward edge of the plate into the flow path of the hole. The final feature is the massive shell shape. From Figure 36 (b), it can be seen that the shell shape has a flat bottom that builds up from the plane of the plate. It can also be seen that the shell constitutes the bulk of the mass of the deposit.

Figure 36: Isolated 0-10 (II) Structure

All of the deposit structures in Figure 35 a)-d) create 25 % reduction in mass flow despite having different structure shapes and sizes. Since the large structure in Figure 33

d) creates the same blockage as the wedge shapes, it can be deduced the only portion of the dust that causes blockage is the dust that causes a restriction in the hole. This would only be the dust that deposits in the hole. Figure 37 shows a notional cross-sectional schematic of the deposits within the hole. All of the wedge shaped structures extend from the plate surface plane down to the bottom surface of the hole. The front faces of the 0-10 (II) and 5-10 distributions are concave and do not directly extend to the bottom surface of the hole.

Figure 37: Cross-Sectional Schematic of a) Wedge, b) Structure Formed with 5-10 μm ARD, c) Scoop Structures

The shape that develops outside the hole will have an influence on the flow streamlines entering the hole and alter where the dust will impact. Small dust that follow streamlines will continue to follow the streamlines but the larger particles will likely be affected by this change in flow. To better understand how the structures form, a better understanding of how the large particles interact with the structure is required.

4.2: Sequential Dust Tests

In order to gain the understanding of how large particles affect blockage, a series of tests were conducted in which two different dust size distributions were sequentially

injected. First 0-10 (II) was delivered to build up structures and cause a 25% reduction in mass flow. Then while the rig was still at the test conditions, an equivalent mass of the 5-10 or 10-20 μm distributions were injected. Since the second dust distributions do not have the small particles that likely cause blockage, these tests show the effects of large particles by themselves.

4.2.1: Test Conditions and Preliminary Data

The test conditions for the sequentially loaded dust tests were the same as the single dust tests. Similar to the single dust tests, insight can be gained from analyzing the reduction history plots shown in Figure 38. There are three distinct periods that show up in the reduction history. First is the initial blockage when the 0-10 (II) is injected. R increases relatively linearly during this period until it reaches at least 25 when the dust stops being injected. Then the feedbox is opened up and the secondary dust is loaded. This dust transition interval shows up as a flat period where the R doesn't change. Since no dust is being delivered and R doesn't change, this indicates that the flow itself does not naturally reduce R by itself. The transition period is followed by a reduction in R. This occurs as soon as the larger dust begins to be injected.

It should be noted that the four erosion tests required on average 0.46 grams of 0-10 (II) to block to 25%. This is less dust than was required in the single dust study and corresponds to an average BPG of 56. If plotted alongside the other 0-10 (II) data in Figure 34, these tests would lie slightly above the linear fit line. This would not change the observation that BPG for this geometry has a first order dependency on ω_d below 3 μm .

Figure 38: R History for Sequential Dust Loading Tests

In Table 14 the initial R , final R , and change in R are reported for the sake of easily comparing the tests. From this data, it can be seen that both of the larger dust distributions can significantly reduce the amount of blockage in a hole. Both distributions reduce R by a comparable amount with the 10-20 μm distribution reducing R slightly more than the 5-10 μm distribution. This indicates that physics governing the reduction in R isn't very different between particles between 5-10 μm and 10-20 μm in this flow field. One way of assessing the difference between these results is by looking at how the deposit structures change after the large dust has been injected.

Table 14: Sequential Dust Loading Test Data

Secondary Dust Type	Test Number	Initial R	Final R	Delta R
5-10	1	27.4	16.3	11.1
	2	26.0	17.0	9.0
10-20	1	23.6	10.6	13.0
	2	26.6	13.2	13.4

4.2.2: Deposit Structure Discussion

Figure 39 shows representative examples of dust structures formed by 0-10 (II) alone, 0-10 (II) followed by 5-10, and 0-10 (II) followed by 10-20. Figure 39 a) serves as a baseline for comparison for the other images. All of the same conventions used in Figure 35 are used here as well. The first observations that can be made are about the size of the deposits. The heights of the deposits from the surface of the plate to the top of the deposit were measured using the microscope's Z-axis indicator. The non-dimensional deposit heights are shown in Table 15. It can be seen that the H/D of the eroded structures are smaller in all cases. Additionally, the front faces recede and the deposit width decreases.

Table 15: Non-Dimensional Deposit Height for Erosion Tests

Primary Dust	Secondary Dust	Test Number	H/D
0-10 (II)	N/A	1	0.82
		2	0.68
	5-10	1	0.56
		2	0.56
	10-20	1	0.40
		2	0.52

These are all indications that the larger dust is eroding the structures. Looking specifically at Figure 39 b), the front face shows a slight recession from the windward edge of the hole inlet. The front edge has a slight taper from the widest point in the deposit which is not seen in the baseline deposit. Figure 39 c) exhibits similar behavior but to a larger degree. The front face of this deposit only extends half way into the inlet flow path. Instead of a rounded edge that obscures the hole, it has a concave front edge that allows visual access to the hole. In the hole, a dark “Y” shape appears. Remembering that the dust is a light tan color and the plate is a dark blue color, this “Y” shape is the bottom surface of the hole. In this region the tongue of the baseline structure forms.

Since the bottom surface of the hole can be seen, this means that the 10-20 μm dust eroded away part of the tongue in the dark “Y” region. This reduces the area constriction in the hole and can explain the reduction in R. The deposit in Figure 39 b) also saw a similar level of reduction in R as the deposit in Figure 39 c), thus it must also have a reduced hole constriction as well. Although it can’t be seen, it can be inferred that the tongue on this structure is also eroded to some degree.

Figure 39: 5x Magnification of Deposit Structures with Dust Loading of a) 0-10 (II), b) 0-10 (II) followed by 5-10, c) 0-10 (II) followed by 10-20

This erosion data was taken after a structure was completely built up. Since the larger dust doesn't stick to the deposit structure, these particles are likely eroding the structure as it builds up. This would change the shape and size of the structures as they grow which in turn would influence how the structures interact with the flow. This can explain the difference in the shape of the structures seen in Figure 35. In the case of the 0-3 and 0-5 μm distributions, the small dust impacts the hole surface as it attempts to

navigate the aggressive turn. There isn't dust in the distribution large enough to erode the structures so the structures are able to grow unimpeded. This results in a small amount of mass creating considerable blockage. The 0-10 μm distributions have a mix of particles that deposit and erode. 0-10 (I) has a greater mass fraction of small dust that deposits in the hole. Some of this dust will get cleared away from the larger dust in this distribution creating a wedge shape that doesn't extend as far into the flow path of the hole and has a broader base than the smaller distributions. The larger dust may also be responsible for the change in texture between the 0-10 (I) wedge and the smaller wedges. 0-10 (I) appears smoother and has crisper lines than the other wedges. The large dust would likely break asperities as they form preventing a jagged appearance seen in the 0-3 and 0-5 wedges. 0-10 (II) has a small mass fraction of dust that is likely to deposit in the hole while having a greater amount of dust that causes erosion. Some of the dust that sticks in the hole gets cleared away by the larger particles. This prevents the structure from building straight up from the bottom surface of the hole like the wedges. As these two processes happen, the developing structure changes the direction of the flow which causes particles that don't make it into the hole to impact the plate surface and top of the deposit. These areas grow, further changing the flow and creating the large shell-shaped structure seen experimentally. The 5-10 μm has a small amount of dust that sticks in the hole and large mass fraction of dust that can cause erosion. As a result, the small dust that deposits in the hole gets cleared away by the larger dust. The only area that dust accumulates is on the leeward edge of the hole where larger particles don't impact.

4.3: Context of Results

The finding that blockage is dependent on the mass fraction below $3\text{ }\mu\text{m}$ in diameter has implications for comparing experiments done in the open literature to each other. There isn't a universally agreed upon size distribution or type of dust used for these kinds of experiments. As a result, the dust size distributions and chemical compositions vary from study to study which makes direct comparisons of blockage across studies difficult. Even a small change in mass median diameter seen in the 0-10 distributions can create very different blockage results. Chemical composition of the test dust used will also directly impact the material properties of the dust. Particles with lower yield stresses will lose more energy during the deformation process that occurs on impact. This results in greater contact area and lower rebound energy which both increase the likelihood of a particle sticking. This would allow larger particles to stick to the surface instead of rebounding and thus change the critical diameter for deposition.

Despite these difficulties, comparisons can be made between these experiments and studies in the open literature. In a nozzle guide vane leading edge simulator, the critical deposition diameter for ARD was found to be around $3.25\text{ }\mu\text{m}$ which agrees well with what was found in this body of work [15]. Interestingly, the BPG_A didn't collapse as well for the leading edge simulator geometry. Even after normalizing by the mass below $3.25\text{ }\mu\text{m}$, the larger distributions investigated showed lower BPG_A . This prompted a study of the effects of larger particles on blockage. This study sequentially loaded different size distributions of dust and found that 5-10 and 10-20 μm distributions both reduced blockage. The 5-10 μm distribution had a greater ability to clear away the hole blockage

than the 10-20 μm distribution. This phenomenon was attributed to the 5-10 μm particles being able to more easily follow streamlines and impact the deposit structures. This mechanism then is dependent on the flow in the cooling geometry which is set up by the cooling geometry itself. This highlights the importance of creating accurate models that can predict deposition numerically. In this way, a designer can investigate a geometry's susceptibility to deposition.

The results from these experiments contradict the results found by Walsh et al. [20] in a cylindrical film cooling geometry. Due to differences in flow area, pressure ratio, and dust size a direct comparison of BPG can't be made between Walsh et al. and the data in this study although the trends with particle diameter can still be examined. They found that for ISO 12103-1 test dust, increasing mean diameter of the particles over the range of 18.5 μm to 50 μm increased blockage for the same mass of dust injected. They hypothesized that the large particles, which could be on the order of half the diameter of a hole, will impact with a lower velocity. This results in less stored energy used for rebounding off the surface. If the adhesion energy is greater than the stored potential energy then the particles will stick to the surface. Due to the large mass of these particles, they will have high stored energy but if just a few of these very large particles stick, they would create significant blockage due to the size of the particle. Since most of the particles that pass through a compressor stage are on the order of 3 to 6 μm [3], the large particle sizes investigated by Walsh et al. [20] may not be as relevant to internal deposition as the distributions used in this study. Although those sizes may not be as relevant for predicting internal deposition, it shows the complex nature of internal

deposition. This again highlights the need for a robust model that can accurately represent the physics of deposition so that prediction of blockage can be made.

Chapter 5. Numerical Results

5.1: Clean Two Hole Simulation

5.1.1: Flow Solution

To better understand the impact and sticking locations of the particles injected during the experiments, 3D RANS simulations were conducted on a two hole geometry that represented a small section of the experimental effusion cooling array. The first domain analyzed is the clean hole geometry. The flow solution along the mid-plane of the front and back hole can be found in Figure 40. The direction of the flow in all of the contours is left to right. The flow accelerates into the holes and separates off the sharp 150° expansion corner creating a bubble of low momentum fluid. The separated flow accelerates along the leeward side of the hole and reattaches to the windward side before jetting into the domain outlet. Where the flow separates and attaches to the leeward side of the hole corresponds to where the deposits build experimentally.

Figure 40: Velocity Magnitude through Mid-planes of the a) First and b) Second Clean Hole

The streamlines of the flow near the hole inlets show that most of the mass flow above $4 D_e$ completely bypasses the holes and exits the primary outlet. The flow that does turn into the holes has a small radius of curvature as can be seen in Figure 41. It is in this

zone that particles are likely to start acting ballistically and not follow the flow into the holes.

Figure 41: Clean Two Hole Flow Streamlines

5.1.2: Particle Injection

After the flow solution was found, particles ranging in size from 0.5-20 μm were injected into the flow. The Lagrangian solver predicted how particles would move through the flow and tracked their trajectories. A total of 56,000 particles (2,000 of each size) were placed in the inlet at random locations within $4 D_e$ of the plate surface. The flow above $4 D_e$ did not turn into the holes and thus particles injected above $4 D_e$ would follow the flow out the primary exit without interacting with the plate. The primary goal of this study is to visualize deposition and make projections regarding hole blockage

locations. Since only particles that interact with the plate surface can cause blockage, any non-participating particle is not of interest and thus not modeled.

As previously discussed, the OSU deposition model with a variable particle yield strength dependent on velocity was used to determine if particles stuck to the surface. Particle impacts and sticks were recorded spatially along the plate. From this data, important parameters such as impact efficiency, capture efficiency, and sticking efficiency of different particle sizes can be determine. Impact efficiency quantifies the likelihood that a particle will hit the plate and is defined in Equation 14 as the number of particles of a certain size that hit the plate divided by the number of particles of that size injected into the flow. Capture efficiency is similar to impact efficiency but instead of impacts, it looks at the number of particles that stick. Taking the ratio of capture efficiency and impact efficiency gives a particle's sticking efficiency. This quantity details how likely a particle that impacts the surface will stick. These efficiencies are shown in Equations 14-16.

$$\eta_I = \frac{N_{impacts}}{N_{injected}} \quad 14$$

$$\eta_C = \frac{N_{stick}}{N_{injected}} \quad 15$$

$$\eta_S = \frac{N_{stick}}{N_{impacts}} \quad 16$$

Figure 42 shows a plot of the efficiencies for both the model with a variable yield strength (σ_y) and a constant σ_y for the first time a particle impacts. Since the deposits in and around the holes play a role in blockage, only impacts in the hole and within 1 D_e of the hole are counted for $N_{impacts}$ and N_{sticks} in the efficiency calculations. The total number

of particles injected for each size is used for N_{injected} . The first thing to notice is that impact efficiency decreases monotonically as particle size increases with the exception of the 0.5 μm particles. This is an interesting observation and can be explained by looking at the particle path lines. Figure 43 -Figure 46 show traces of particle path lines through the clean hole domain. The path lines are colored black with a low opacity which allows one to see the trends in particle trajectories. When the path lines of multiple particles overlap, the region gets shaded darker and from this, the relative concentration of particles can be observed.

Figure 42: Clean Two Hole Capture, Impact, and Sticking Efficiency

Figure 43: 0.5 μm Path Lines through Clean Two Hole Domain

Figure 44: 3 μm Path Lines through Clean Two Hole Domain

Figure 45: 6 μm Path Lines through First Clean Hole

Figure 46: 10 μm Path Lines through Clean Two Hole Domain

Figure 43 shows that most of the 0.5 μm particles are able to successfully navigate the turn into the hole without impacting on a surface. Particles in the range of 1-

$5.5\text{ }\mu\text{m}$ are unable to completely navigate the turn and impact in the hole inlet. Figure 44 shows that $3\text{ }\mu\text{m}$ particles impact in the hole just upstream of where the highest fluid velocity is seen in Figure 40. The acceleration in the jet region is too sudden for the drag on the particles to overcome the inertia of the particles which results in the particles hitting the hole surface. Some of these particles stick while the remaining particles rebound off the surface and exit the hole. As the particles get larger, they have a more difficult time turning with the flow and thus impact further up the hole inlet. Figure 45 shows the impacts of $6\text{ }\mu\text{m}$ particles in the first hole. Here it can be seen that the particles impact all along the inlet whereas the $3\text{ }\mu\text{m}$ particles were concentrated in one region. The $6\text{ }\mu\text{m}$ particles rebound further off the surface before being re-entrained in the flow. This shows up as the curved paths after impacting the surface. This behavior continues as particles grow in size. Figure 46 shows the trajectories of $10\text{ }\mu\text{m}$ particles which impact further downstream than the hole inlet. The path lines are lighter which indicates few particles are making it into the hole. Since they are not impacting in the hole, the impacts further downstream on the plate are not counted in the impact efficiency plot. This results in the decrease in impact efficiency as particles increase in size. In order to see how impact location changes with particle diameter, Figure 47 shows a contour plot of the local impact efficiency as a function of diameter and distance from the leeward edge of the hole inlet. The length of the hole is broken up into bins and the local impact efficiency uses the number of impacts within these bins as N_{impact} for each diameter. N_{injected} is defined here as the total number of particle hits in the hole and within 1 D past the leeward edge for each diameter. This allows one to see where particles are most likely

to impact within the cooling hole. The distance from the leeward edge of the hole (S) is non-dimensionalized by the hole diameter to give a ratio of S/D . A positive S/D represents a distance into the hole where as a negative S/D is a location outside of the hole past the leeward edge.

Figure 47: Local Impact Efficiency as a Function of Particle Diameter and Non-Dimensional Distance from the Leeward Edge of the Hole Inlet

The second thing to notice is that the capture and sticking efficiencies of both yielding models agree well for particles with diameters larger than 6.5 μm . Below this size, the variable σ_y model predicts more particle sticks than the constant σ_y model except for 1-1.5 μm particles. The reason for this is in the formulation of variable σ_y model. The

variable σ_y model has a lower threshold σ_y of 100 MPa. A particle must have a velocity of at least 28 m/s to overcome the initial 100 MPa threshold but will still have a lower σ_y than the constant σ_y until the particle reaches 40 m/s. At 40 m/s, both models have a σ_y of 145 MPa. Once a particle has a velocity higher than 40 m/s, the σ_y increases proportionally to impact velocity. Plotting the mean, standard deviation, and a histogram of particle velocity in Figure 48 Figure 50 offers an explanation for the non-monotonic behavior of small particles. It can be seen that only the 1-1.5 μm particles have a mean velocity higher than 40 m/s. As particles get larger, the mean and standard deviation of the impact velocity decreases. This means that most of the particles impact with a lower σ_y with the variable σ_y case than the constant σ_y case. With a lower σ_y , the energy lost to plastic deformation increases and the particle has less energy to rebound. For particles larger than 6.5 μm , the work of adhesion is low enough that the lower σ_y doesn't seem to have a large effect but this isn't the case for particles smaller than 6.5 μm . The non-recoverable plastic deformation energy reduces the rebound energy for the small particles below the work of adhesion. This results in more particles sticking to the surface. The exception to this is 1-1.5 μm particles. Figure 50 illustrates that more than half of the 1 μm particles have impact velocities greater than 40 m/s. These particles have larger σ_y and lose less energy to plastic deformation which results in less particles sticking.

Figure 48: Clean Two Hole Particle Mean Impact Velocity vs Diameter

Figure 49: Clean Two Hole Particle Impact Velocity Standard Deviation vs Diameter

Figure 50: Histogram of Impact Velocity for 1 μ m Particles in Clean Two Hole Domain

In order to better determine the effects of the variable yield strength formulation, an additional case of particle injection was conducted with a constant yield strength of 100 MPa. This was done to eliminate the σ_y thresholds that appear when comparing the previous data. The efficiency data for this case are plotted with the previous data in Figure 51. Here it can be seen that the variable yield strength and the lower constant σ_y match for 0.5 μ m particles and those greater than 5 μ m. Particles between 0.5 and 5 μ m start to have velocities that allows the variable σ_y to exceed 100 MPa. At this point, the variable σ_y strengthens the particles and prevents particle sticking. This shows that choosing the appropriate material properties has a strong impact on the modeling results.

Figure 51: Clean Two Hole Capture, Impact, and Sticking Efficiency with $\sigma_y=100$ MPa

The constant σ_y of 145 MPa does not show a large difference in sticking or capture efficiency for all the particle sizes investigated. This suggests that a similar number of each particle size undergoes enough plastic deformation to produce sticking in the near hole region. This isn't what was seen experimentally. Experimentally, the particles between 0-5 μm were seen to stick in the hole causing blockage while particles between 5-10 μm had erosive behavior with little deposition in the hole. This indicates a deficiency in using this constant σ_y for the model.

Looking at the variable σ_y data in Figure 42, the particles can be divided into two main groups: particles that are likely to stick, sticking efficiency greater than 40%, and

particles that are not likely to stick. In general, particles below 5 μm in diameter are the most likely to stick. These particles also have higher impact efficiency near the hole which means that these particles likely cause deposit build up. Knowing the sticking and capture efficiencies is useful for quantitative comparison of the different particle diameters but it doesn't detail where the particles are hitting or sticking. Physical location of sticks is important because this is where deposits would build and cause blockage. Figure 52 compares the impact and sticking locations for the first group of particles when the variable σ_y model is used. In all of the images, the flow direction is from left to right.

Figure 52: a) Impact and b) Sticking Locations of 0.5-5 μm Particles in Clean Two Hole Domain

It can be seen that the particles impact within the hole or near the leeward edge. The sticking locations look very similar to the impact locations which mean most of the

particles that impact in this region are sticking with the exception of the 1-1.5 μm particles. This sticking region looks like where the deposits built up experimentally with the 0-3 and 0-5 μm dust distributions. Superimposing the deposit picture onto the sticking locations, Figure 53 shows that there is reasonable agreement between predicted sticking locations and experimental deposit growth. In the experimental portion of the comparison, the structure that builds is a wedge that extends from the surface of the plate down to the bottom surface of the hole. Additionally, there is a coating of dust covering the bottom of the hole. The predicted sticking concentrates along the center line of the hole and fans out further along the hole. Particles are not predicted to stick near the tip of the wedge and the model under predicts the width of the wedge base that accumulates along the leeward edge of the hole.

Figure 53: Comparison of Experimental Structure to Predicted Sticking Locations

There are a variety of reasons for these discrepancies. First, it is important to note that the predicted sticking is modeling an initial layer of dust on a smooth surface. A

particle impacting an aggregate of particles will likely have more contact area that adhesion can act on than a particle impacting a solid surface. This would increase the required energy to rebound off the surface and thus promote sticking. Additionally, the particles on the structure's surface would be held together with adhesion bonds which are likely weaker than the bonds between atoms in a homogenous material. A consequence of this is that a structure could yield before the impacting particle and change in shape. The work to change the structure shape would have to come from the impacting particle which would reduce the available energy to rebound. This would increase the amount of particles sticking but also could result in removing mass from the structure. Once the structure starts to take shape it will also change the flow direction as will be discussed later in this chapter. These could be reasons for the morphological differences between the experimental structure and the predicted sticking pattern.

Similar to the small particles, the impact and sticking locations of the group of large particles are shown in Figure 54. Here it can be seen that there are significant number of large particle impacts in the same region that the small particles deposit. The difference with this second group is that not as many of the particles stick. If a particle has high enough incoming energy, it would be able to remove mass from an existing structure in addition to rebounding from the surface. It was seen experimentally that large particles have the capability to erode and shape the structures. This indicates that particles in the range shown do in fact have enough energy to break the adhesion bonds in the structure.

Figure 54: a) Impact and b) Sticking Locations of 5.5-20 μm Particles in Clean Two Hole Domain

Interestingly, the CFD study predicts large particles sticking in a line after the hole. This isn't seen experimentally. There are a few reasons why this could be happening. Particles remain in the fluid domain after they rebound off the surface and impact the surface multiple times. After a particle rebounds, it has less energy on subsequent impacts. This means that particles can impact multiple times before sticking to the plate surface. If a particle is impacting multiple times, it would also have the possibility of eroding any deposited dust with every impact. The model in its current form does not

account for erosion of deposits by particles. This means that there could also be erosion in the same region after the hole that isn't being calculated and reported.

Another possible reason that the dust isn't seen in a line after the hole is that once the deposit builds in the hole, the flow changes enough that the large particles no longer hit there. The following section investigates the effect that a scoop structure has on the flow field and particle trajectories.

5.2: Scoop Hole Simulation

5.2.1: Flow Solution

Scoop shapes that represent the structures seen in the 0-10 (II) experiments were inserted into the clean hole geometry to see the effects that the structures have on the flow field and particle trajectories. This grid adaption strategy is a simplified mesh morphing technique that allows one to gain insight on particle behavior after deposition has occurred. The advantage to this method is that it doesn't employ deposition models or complicated mesh morphing algorithms that haven't reached full maturity yet. The primary disadvantage associated with this kind of grid adaption is the user input. The structure shapes are estimated based on pictures and are not known a priori. This restricts the method to the explanatory domain and can't be used for predictive modeling during the design process.

Inserting the structures into the clean hole domain changed the flow near the hole but had little effect on the velocity field more than $3 D_e$ above the plate surface. The magnitude of the velocity near the holes can be seen in Figure 55. The scoops primarily

influenced how the flow entered the hole. The scoop structure reduces the size of the hole inlet which reduces the mass flow rate through the hole. The flow still separates off the windward hole edge and accelerates the flow into the hole with a jetting effect. The maximum velocity changes by less than 1% with the introduction of the structures.

Figure 55: Velocity Magnitude through Mid-planes of a) Front Scoop Hole, b) Front Clean Hole

Comparing Figure 55 a) to Figure 55 c), it is apparent that once the flow reattaches to hole, the scooped hole has slower and more uniform flow velocity. This corresponds with an 18% reduction in mass flow at the exit of the hole. This is not as much of a reduction in mass flow as was seen experimentally. This discrepancy isn't

surprising given that this scoop shape isn't exactly the same as the experimental structure and highlights a disadvantage of this type of grid adaption technique. It is difficult to create replicas of physically built structures using images of the structures. Although the mass flow reduction isn't matched exactly, the scooped domain will still show the effects that a structure of similar size and shape has on the flow and particle trajectories. This can still provide insight into the formation of these structures.

5.2.2: Particle Injection

Particles were introduced to the scooped hole domain in the same manner as the clean hole domain. 56,000 particles were randomly placed at the domain inlet and a Lagrangian solver tracked the particles through the domain until the OSU deposition model determined the particles stuck to a surface or the particles exited through the outlets. Particle impact and sticking locations were recorded along the surface of the geometry. Impact, capture, and sticking efficiency were calculated from the particle initial impacts in and around the holes and are shown in Figure 56. The impact efficiency shows a similar monotonic trend with diameter seen in the clean hole geometry but with more impacts for the larger particles. Looking at an impact map and particle path lines, it can be seen why.

Figure 56: Scoop Hole Capture, Impact, and Sticking Efficiency

Figure 57: Trimetric View of Impacts on Scoop Domain

Figure 57 shows a trimetric view of the scoop geometry looking in the inlet and coloring particle impacts by size. The scoop structures sit $1 D_e$ above the plate and are $2 D_e$ wide. Particles unable to turn into the clean hole hit the face of the scoop. This prevents the particles from impacting the plate further downstream as was seen in the clean hole geometry. The shadow region it creates could also be a contributing factor to the lack of particle deposits witnessed experimentally immediately behind the holes. When the particles impact the scoop surface, they can be deflected into the hole as seen in Figure 58. The scoops and holes are colored green for ease of visualization. $10 \mu\text{m}$ particles are seen to impact on the face of the scoop and rebound into the hole. Some of the path lines appear to rebound more than once in different locations in the hole. This indicates not very much energy is lost during plastic deformation with respect to the adhesion that the particle must overcome. This excess energy would likely cause erosion in an actual deposit. Looking at the trajectories, the scoop appears to redirect the particles into the tongue section of the structure. This has implications for why the tongues do not develop into a wedge, as seen with other size distributions in the experiments.

Figure 58: 10 μm Path Lines through Scoop Hole Domain

The sticking and capture efficiency for the variable σ_y case show similar behavior as was seen in the clean hole case. The highest sticking occurs for particles less than 5 μm in diameter with the exception of 1-1.5 μm particles. Plotting the mean impact velocity in Figure 59 shows that these particles are exceeding 40 m/s and thus have a higher σ_y than 145 MPa. It follows the same logic as in the clean hole case that these particles are not predicted to stick. Interestingly, these particles stick more when using a constant σ_y which wasn't seen in the clean hole geometry. The reason for this is the angle at which the particles impact the surface. The deposition model has a term that attenuates the adhesion acting on a particle by the sine of the incidence angle which is defined as the angle at which the particle strikes the surface. This accounts for particles that hit with high tangential velocity but low normal velocity are not likely to stick to a surface. Figure 60 shows the mean incidence angle for a given particle size in both the clean hole

geometry and the scooped hole geometry. It shows that in the clean hole geometry, the particles between 1-1.5 μm in diameter impact with low incidence angles. This would result in low adhesion and thus the low sticking efficiency seen for these particles.

Figure 59: Scoop Hole Particle Impact Velocity Standard Deviation vs Diameter

Figure 60: Comparison of Mean Particle Incidence Angle vs Diameter

The particles impact at a steeper incidence angle in the scooped hole geometry than in the clean hole geometry. Higher incidence angles result in higher adhesion acting on the particles in the model which increases particle sticking. This coupling between particle sticking behavior and structure shape highlights the importance of accurately modeling deposit structures when predicting sticking during the design phase. A cooling design may be assessed using a deposition model for its resistance to blockage development. If only an initial layer is assessed, i.e. a clean geometry, the results of the study will not reflect the actual deposit build up and the coupling associated with it. In the worst case scenario, the design study would severely under predict sticking and a part could not work as expected and potentially fail.

5.3: Scanning Electron Microscope Size Comparison

One final method of assessing the data processing method and numerical predictions is to physically look at what particles are sticking in the tongue and scoop section of the deposits. To do so, scanning electron microscope images were taken of a number of tongues and scoops separately at the Ohio State University Campus Microscopy and Image Facility. Whole deposits from a 0-10 (II) test were pushed out onto a slide and with the aid of a magnifying glass, the tongues were separated from the scoops with a razor. The different parts of the deposit were then imaged on separate mounts. During of the mounting process, tongues and scoops were compressed and broken into small piles of dust. Figure 61 a) and c) show different locations along a broken tongue specimen at the same magnification. These images were chosen to show the extremes in particle sizes witnessed across the images taken. The particles in Figure 61 a) are larger than the particles in Figure 61 c) indicating that location along the tongue has an influence on which particles stick. Unfortunately, since the structures were broken while mounting on an SEM stem, the exact location on the tongue is unknown for these images. Figure 61 b) looks at the red box region in Figure 61 a) at a higher magnification. The white lines are 10 μm scale bars added for reference. It can be seen that the largest particles are around 6 μm in size with the smallest particles being a fraction of a micron.

Figure 61: Scanning Electron Microscope Images of Particles that Comprise the Tongue Deposit Feature formed with 0-10 μm (II) ARD

Using the image analysis software MIPAR, Figure 61 a) and c) were segmented to isolate and measure the individual particles. The results of this process can be seen in Figure 62 with the particles being colored by equivalent diameter. The equivalent diameter is the diameter of a circle that contains the same area as the particles in the

image. Here it can be seen that with the software, the particles are successfully identified. A histogram of equivalent diameter is shown in Figure 63 for these images.

Figure 62: Particle Segmentation of Scanning Electron Microscope Images of a) Tongue Deposit Feature 1, b) Tongue Deposit Feature 2

From the histograms, it can be seen that the majority of the particles identified are smaller than $3\text{ }\mu\text{m}$. Tongue image 2 has a greater quantity of small particles which one would expect from looking at the images. These are the particles that the experimental data suggest are primarily responsible for blockage. The presence of particles larger than $3\text{ }\mu\text{m}$ indicates that there isn't a hard cut off for particle sticking by size. The mechanics for hole blockage are more complicated than an empirical cut off but these images support the idea that the majority of the particles that deposit within these holes, and cause flow blockage, are around $3\text{ }\mu\text{m}$ in diameter.

Figure 63: Histograms of Equivalent Particle Diameter for a) Tongue Image 1, b) Tongue Image 2

Figure 64 a) and c) show the images taken of the scoop at different locations at the same magnification. These images have a larger range in particles sizes than seen in the tongues. There doesn't appear to be as much variation in particle size based on location along the broken deposit. Particles from all along the particle size distribution are represented although there does appear to be less of the largest particles. Figure 64 b) zooms into the red box region of Figure 64 a). The white lines again are 10 μm scale bars. The largest particles seen are on the order of 10 μm which is on the edge of the particle size distribution. This is not surprising when considering the different measurement methods used. The particle size distributions provided by the manufacturer are created using a Coulter counter which reports an effective spherical particle diameter using the volume of the particle. The measurement taken above shows one dimension of the particle. Long flat particles have less volume than a sphere with a diameter of the same size as the longest dimension of the particle. This results in the particles appearing larger

using a single length than the reported equivalent diameter. This also occurs when analyzing the images using MIPAR to find the particle area.

Figure 64: Scanning Electron Microscope Images of Particles that Comprise the Scoop Deposit Feature formed with 0-10 μm (II) ARD

The same process to identify and size particles was used on these images and the histograms of equivalent diameter can be seen in Figure 65. The scoops have slightly

larger particles with the majority being below 4 μm . There are some particles as large as 7-8 μm . Although not as many, the presence of large particles would increase the volume, and thus size, of the scoop structures.

Figure 65: Histograms of Equivalent Particle Diameter for a) Scoop Image 1, b) Scoop Image 2

This shows that the scoop is still primarily made of small particles. The CFD predicts that large particles are impacting the scoop and so the lack of large particles could be understood a few ways. The first thought is that while large particles can stick, they are much more likely to rebound. This behavior can explain why the tongue is curved instead of a wedge. Since these large particles are not seen in the tongues, if a large particle rebounds off the scoop face into the hole then it will rebound off the tongue and/or erode it away. If a wedge were to start building up, subsequent impacts by large particles prevent the tongue from growing as rapidly. In the case of the sequential dust

tests, there wasn't small dust in the secondary dust. This resulted in the erosion of the tongue without dust to restore it.

Chapter 6. Conclusion

Experiments were conducted in an accelerated deposition facility to investigate the effect of particle size on internal deposition in an effusion cooling geometry. An effusion plate was heated to 1118 K and cooled with dust laden air at an engine relevant temperature and a constant pressure ratio. It was seen that particle diameter over the range of 0-10 μm had a first order effect on normalized blockage. Through weighting the dust distributions by mass fraction below a certain diameter it was found that the dust below 3 μm in diameter was primarily responsible for flow blockage in the cooling holes. Tests done by sequentially loading larger dust distributions after 0-10 (II) showed that large particles can have an erosive effect on particle deposit structures. This results in a reduction in flow blockage and a recovery in mass flow.

Computational simulations were conducted on simplified cooling array domains representing clean holes and holes partially blocked by deposits. Particles were injected into the converged solutions and tracked with a Lagrangian particle trajectory solver native to the commercial software. A physics based deposition model from the open literature was used to determine the rebounding and sticking behavior of particles that impact the surface. This model is dependent on material properties that are difficult to experimentally evaluate. As such, two different yield strength formulations were used based on experiments conducted using this model. It was seen that small particles were

most likely to impact and stick within the hole. The rate at which different particle sizes stuck depended on the yield strength formulation. Using different constant yield strengths resulted in different sticking behavior for small particles. Using variable yield strength increased the sticking efficiency for particles below 5 μm in diameter when compared to the higher constant yield strength except for those particles which hit with high velocities and low incidence angles. The particles that were strengthened by the variable yield strength saw lower sticking rates than when a lower constant yield strength was used. This resulted in an overestimate of the size of the most important particles for flow blockage. Introducing representative deposit structures to the flow domain showed that deposit build up can change particle trajectories and impact behavior.

This body of work is a stepping stone in the understanding and high fidelity modeling of particle deposition in gas turbines. The difficulties of accurately modeling deposition encountered here point to the following as possible areas of fruitful research moving forward.

1. There were discrepancies between the mass flow seen experimentally and those found numerically for the same conditions. A more sophisticated computational fluid dynamics solver may be a key to better matching the flow through these types of geometries characterized by separated flow.
2. The grid adaption method used here was useful to gain insight on the coupling between deposit structures and particle impact behavior but is not a viable method for predictive modeling on novel geometries. Dynamic mesh morphing is a more promising grid adaption strategy that can be pursued.

3. In order to inform a dynamic mesh morphing technique, a deposition model must be used. Possible avenues to improve the current models are including the effects of erosion, including material properties that reflect that a deposit structure is an aggregate of particles, and investigating the physical dependencies of adhesion.
4. This study only looked at the effect of particle size on deposition. There is still very little information in the open literature on the effect geometry has on deposition. As cooling schemes move to smaller more complicated shapes and configurations, the possibility that deposit structures can disrupt an intended design increases. Quantifying the effect geometry has on deposition rates as well as deposition's effect on the intended cooling design could also prove to be a useful research thrust to inform designers.
5. It was assumed that all the particles were of the same composition. It is possible that the different compounds that compose the dust show up as different sized particles. A future study investigating if there is coupling between particle size and composition could help to better assess the effects of particulate composition.

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