

Onset of Arizona Road Dust Deposits in High Temperature Environment on a Cooled HASTELLOY® X Surface

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ABSTRACT

Experimental testing was performed on the Virginia Tech Aerothermal Rig using a water-cooled sudden-expansion burner located at the Advanced Propulsion and Power Lab. The purpose of the study was to quantify the onset of deposit formation to aid in the development of resilient engine design and operational diagnostics. Testing was conducted using flat HASTELLOY® X coupons and Arizona Road Dust sample with sizing between 2 μ m and 40 μ m at gas path temperatures between 1050°C and 1100°C. Three cooling testing conditions of no cooling, 500°C cooling, and 250°C cooling were used to alter the coupon surface temperatures. Testing bulk velocity and impact angle were kept at a constant 70m/s and 50°, respectively. The objective was to study the sensitivity of the onset of deposits to provide insight into the response of deposits. Microscopic images were quantified by using a semi-autonomous image processing method to count individual particle deposits on test coupons. Although 2 μ m to 40 μ m Arizona Road Dust sample were used for testing, dust sizing between 10 μ m and 19.7 μ m were used for data reduction and analysis. Results from testing indicated that smaller particle deposits between 10 μ m and 14.2 μ m were prominent across all test cases. Results also concluded that internally cooled test conditions affect the steady-state near-surface coupon temperatures and the cooling testing conditions used in this study may not have a first-order effect on particle deposition.

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GENERAL ABSTRACT

In the past several decades there has been an increased interest in sand, dust, and ash particulates ingestion study for gas turbine engine applications. Recently, there has been an increase in commercial and military fleets operating in medium to highly dusty environments, such as areas in Africa, the Middle East, and Asia. Dusty environments can cause blockage in turbine cooling circuits which can lead to early engine maintenance or removals. Ingested debris can melt, forming glassy or molten deposits on various hot section components in gas turbine engines. This thesis evaluates the onset of deposit formation using an experimental rig to perform testing in high temperature environment. In general, deposits on turbine components can affect the operating capacity and the overall operating efficiency of gas turbine engines. Particulate ingestion events can be catastrophic and cost millions of dollars in maintenance and repairs.

The experimental work in this thesis focused only on quantifying the initial deposit formation in high temperature environment to aid in the development of resilient engine design and operational diagnostics. Testing was performed using HASTELLOY® X coupons and Arizona Road Dust with main gas flow temperatures between 1050°C and 1100°C. Arizona Road Dust sample with sizing between 2µm and 40µm were used for experimental testing. The sensitivity of the initial deposit formation on cooled HASTELLOY® X coupon surface was investigated by using an inline air heater. Three cooling test conditions: no cooling, 500°C cooling, and 250°C cooling, were used to alter the surface temperature of the coupon during testing. Results from testing indicated cooling test conditions used have a small impact on deposit formation.

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PREFACE

This thesis is written in a manuscript format and contains one paper directly related to the Master's thesis to be submitted to the Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition. The author is the first author of this paper and was directly involved in all aspects of the experiments described including rebuilding the test rig, planning, setup, testing, data post-processing and analysis. Other details of the work not discussed in the main body of the thesis can be found in the appendix.

Debris ingestion in hot section components have been shown to hinder the performance of gas turbine engines or in severe cases, be the main cause of temporary engine flameout or permanent engine failure. The encountered of gas turbine engine flameouts and failures have led to an increase in studies of debris ingestion. Full-scale and Hot Section Test System testing were performed to quantify the operational lifespan of engines and engine components [1-2]. Testing results explained the interaction between dust and temperatures (gas and metal), but studies examining material interactions with ash and sand were necessary. To study the material interactions with ash and sand, accelerated deposition and erosion testing were performed using ash and Arizona Road Dust on various test coupons and engine hardware [3-7]. Accelerated testing can provide useful insight into the mechanisms responsible for deposit accumulation but evaluating deposits prior to significant accumulation may provide information for improved engine design.

Studies were performed at Virginia Tech to evaluate the initial onset of deposits using uncooled HASTELLOY® X coupons and 20 – 40µm Arizona Road Dust sample [8-12]. A semi-autonomous image processing method was used to count individual particle deposits on test coupons. Deposit data were used to develop an experimental empirical Coverage Ratio model to determine deposit accumulation. A complementing numerical model study was performed to develop a Sticking Probability model. Results from testing were used to establish the onset of deposits, which is the base layer of rapid accumulation. As a continuation of previous deposition studies at Virginia Tech, this study used cooled HASTELLOY® X coupons to decouple particle and surface temperatures which will provide insight into the response of onset deposits.

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ABSTRACT

Experimental testing was performed on the Virginia Tech Aerothermal Rig using a water-cooled sudden-expansion burner located at the Advanced Propulsion and Power Lab. The purpose of the study was to quantify the onset of deposit formation to aid in the development of resilient engine design and operational diagnostics. Testing was conducted using flat HASTELLOY® X coupons and 20 – 40µm Arizona Road Dust sample at gas path temperatures between 1050°C and 1100°C and three cooling testing conditions of no cooling, 500°C cooling, and 250°C cooling. Testing bulk velocity and impact angle were kept at a constant 70m/s and 50°, respectively. The objective was to study the sensitivity of the onset of deposits to provide insight into the response of deposits. Microscopic images were quantified by using a semi-autonomous image processing method to count individual particle deposits on test coupons. Results from testing concluded that internally cooled test conditions affect the steady-state near-surface coupon temperatures and the cooling testing conditions used in this study may not have a first-order effect on particle deposition.

NOMENCLATURE

ARD	Arizona Road Dust
EQT	Equilibrium Tube
CFD	Computational Fluid Dynamics
COR	Coefficient of Restitution
CR	Coverage Ratio
ISO	International Organization for Standardization
HSTS	Hot Section Test System
HX	HASTELLOY® X
NGV	Nozzle Guide Vanes
PIV	Particle Image Velocimetry
PTV	Particle Tracking Velocimetry
PPMW	Parts Per Million by Weight
SP	Sticking Probability
TBC	Thermal Barrier Coating
TIT	Turbine Inlet Temperature
VTAR	Virginia Tech Aerothermal Rig
T _{c,i}	Initial Cooling Air Temperature (°C)
T _c	Backside Cooling Air Temperature (°C)
T _g	Primary Gas (Particle) Path Temperature (°C)
T _s	Near-Surface Coupon Temperature (°C)
V	Flow Velocity (m/s)
θ	Coupon Angle (degrees)

INTRODUCTION

In the past several decades there has been an increasing interest in sand, dust, and ash particulates ingestion study for gas turbine engine applications. A significant portion of commercial and military fleets operate in medium to highly dusty environments, such as areas in Africa, the Middle East, and Asia. Dusty environments can cause blockage in turbine cooling circuits which can lead to early engine maintenance or removals. Deposits on turbine components can affect capacity and the overall efficiency of such engines. Therefore, debris tolerance is a design requirement for hot section components. Figure 1 illustrates a gas turbine operating in dust-laden environment. Ingested debris can melt, forming glassy or molten deposits

on various hot section components or clog film-cooling holes. Deposition in gas turbine hot section components is dependent on several key factors such as aerothermal flow conditions, particulate composition and sizing, and amount of particulates ingested [2]. Due to the increased in operating efficiency of gas turbine engines, there has been an increase in operating temperatures of such engines, causing particulate ingestion into propulsion turbine engines a common event.

Particulate ingestion events can be catastrophic and cost millions of dollars in maintenance and repairs. The increased events of particulate ingestion in commercial and military applications have brought new ways to help mitigate debris ingestions. Pilots were trained on techniques and tactics to avoid volcanic ash clouds [3], and development of satellite and radar systems were employed to warn pilots of possible ash cloud encounters [4]. Increasing service internal frequency, while costly, can be a common way to help mitigate debris ingestion. Another technique used to help mitigate particulate ingestion includes filtration of the intake air and particles separators to help filter out smaller particulates. Unorthodox methods have also been employed, such as rapidly cycling power levels of propulsion engines to induce thermal transient in the turbine airfoils [5].



Figure 1: An example of gas turbines operating in dust-laden environment in California [1].

Experimental testing on full-scale engines has been used in the past to study the erosive effect of debris ingestion. Due to high cost, hot section components and test coupon accelerated erosion and deposition studies are more common and have been widely used in the past decade.

The primary focus of this study is to investigate the initial onset of microparticle deposits on turbine components at near gas turbine hot section temperatures. This study is a continuation of previous work with high temperature microparticle rebounding experiments and modeling [5-12], and microparticle sand sticking probability and coverage ratio [13-16] performed at Virginia Tech. The purpose of the study is to investigate the effect gas path temperature (T_g), also known as particle temperature, and near-surface coupon temperatures (T_s) have on the initial onset of deposition for 20 – 40 μ m Arizona Road Dust (ARD). Particle temperature and surface temperature both play a vital role in the susceptibility of deposition onto a substrate. It is expected that by maintaining particle temperature while decreasing coupon surface temperatures, a thermal gradient will be present. Thermal gradient is the differences between the gas path

temperatures and near-surface coupon temperatures. This increase in thermal gradient between the particle temperature and coupon surface temperatures will aid in the decrease of deposits.

For this study, experiments are performed by injecting ARD at sintering temperature onto an internally cooled HASTELLOY® X (HX) flat plate test coupon at various gas path temperatures and cooling testing conditions. Gas path temperatures are measured using three K-type thermocouples and near-surface coupon temperatures are measured via twelve K-type thermocouples placed on the backside of the test coupon. Particulate deposits are quantified after each experiment. Microscopic images are taken of the test coupon and particulate deposits are quantified by using a semi-autonomous image processing method. Quantifying the onset of deposition at various thermal gradients is crucial to estimating and mitigating subsequent deposits in hot section gas turbine conditions.

RELEVANT PAST STUDIES

Particulate ingestion in hot section components have been shown to hinder the performance of gas turbine engines or in severe cases, be the main cause of temporary engine flameout or permanent engine failure. A flameout is an instance where the flame in the combustion chamber of a jet engine extinguished, resulting in a loss of power. In 1980, an L-100 aircraft encountered two engines failure and two temporary engines flameout while flying over Mount St. Helens after a volcanic eruption [17]. All four engines showed signs of melted dust in the turbine section and severe abrasion in the compressor section. An early instance of temporary engine flameout in gas turbine application was in 1982 on British Airways Flight 9. A Boeing 747, while flying over Mt. Galunggung during a volcanic eruption, was forced to make an emergency landing due to all four engines experiencing temporary engine flameout [18]. Significant erosion and deposition were observed in the turbine section of the Boeing 747 engines. Another example of engine flameout in commercial application took place in 1989 on KLM Flight 867 where a Boeing 747-400 ingested volcanic ash while flying over Mt. Redoubt. An emergency landing procedure took place after all four engines experienced engine flameout condition [19]. All four engines from the Boeing 747-400 were replaced, costing over 80 million dollars in repairs. Particulate ingestion is also a continuing concern for the military sector. In 2015, an Osprey V-22 crashed during a training exercise in Hawaii, claiming the lives of two Marines and injuring twenty other Marines [20]. The cause of the fatal crash was attributed to dust ingestion resulting in an engine failure. A post-accident investigation indicated glassy deposits on the turbine section components to be one of the causes of engine failure. Figure 2 illustrates the Osprey V-22 under flameout condition.

The encountered of gas turbine engine flameout and failure have led to an increase in studies of debris ingestion on full-scale engines and accelerated erosion and deposition testing. Full-scale testing was useful to help understand the responses of propulsion turbines under particulate ingestion. Since erosion and deposition mechanisms are common with debris ingestion, full-scale testing can be used to improve the resilience of propulsion engines. The earliest full-scale engine studies were conducted in 1987 using a TF33 turbofan and J75 turbojet engines. The engines were tested in dust-laden operating condition to evaluate engine performance [22-24]. Deterioration of engines damage consisted of compressor erosion and deposition in the high-pressure turbine, as well as blockage of cooling holes in the high-pressure turbine. However, no glassy deposits were found due to low turbine inlet temperature (TIT) during testing. Full-scale testing was also performed in 1991 on an F-100 turbofan engine to quantify the operational lifespan of an engine in a simulated nuclear dust environment [4]. Damage mechanisms to the F-100 engine consisted of erosion in the cold section and deposition in the hot section. Steps were taken by the operators in this experiment to come up with an unorthodox way to mitigate the buildup of dust deposits. The F-100 engine was put through a thermal transient by rapidly cycling the power levels. In doing so caused the deposited particulate to break free. Unfortunately, the engine was damaged beyond operational capability after long exposure to the dusty testing condition.



Figure 2: An Osprey V-22 experiencing an engine flameout (highlighted by the circle) before crashing during a training exercise in Bellows, Hawaii [21].

To help alleviate the cost of full-scale engine testing while maintaining the same specifications of hot section conditions, a Hot Section Test System (HSTS) was developed. Through the development of HSTS, subsequent testing was performed in 1992 on an F-100 engine annular combustor and nozzle guide vanes (NGV) [2]. Several different blends of dust along with various NGV cooling schemes were used to determine the behavior of engine hardware. Molten deposition was present on the NGV at TIT above 1177°C and metal surface temperature above 816°C . However, no molten deposition was present when TIT was above 1177°C and metal surface temperature below 816°C . Results from testing concluded that deposition was dependent on TIT, surface temperature, and dust composition. Figure 3 illustrates damages to the leading edge of the NGV due to clogged cooling holes. Another study was performed in 1996 using the HSTS F100-PW-220 first stage turbine vanes as well as Inconel 617 film-cooled and Lamilloy® cylinders [25]. Deposition results indicated that molten deposit was present at TIT above 1149°C , unlike the previous HSTS F-100 study which stated 1177°C [2]. However, deposition results indicated that molten deposit was present at metal surface temperature above 816°C , which was in agreement with the previous HSTS F-100 study [2]. Ultimately, the 1996 subsequent HSTS F-100-PW-220 study reaffirm that interaction between particle temperature and surface temperature.

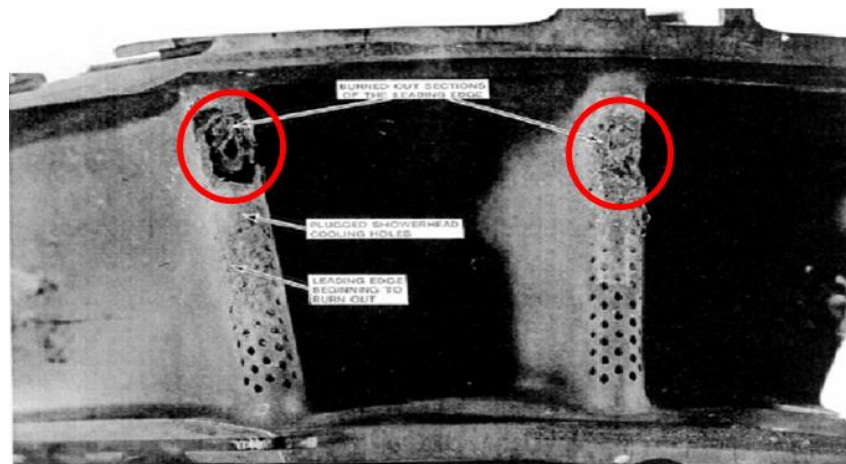


Figure 3: Damages (highlighted by the circles) to the leading edges of the NGV due to clogged cooling holes [2].

Using test coupons to model actual turbine engine hardware have been widely used for accelerated erosion and deposition testing. An accelerated study was performed in 2005 using seed particulate and MCrAlY coated test coupons to simulate 10,000h of turbine operation [26]. Critical testing variables, such as gas temperature and impingement angle, were examined during this study. Deposition results from this study at coupon impingement angles of 30°, 45°, and 90° showed little to no noticeable trend. Deposits accumulation occurred at 900°C gas temperature and increased significantly as gas temperature reached 1100°C. Another accelerated study was performed in 2008 using a test coupon to investigate the independent effect temperatures (gas and metal) and particle size have on deposition [27]. Four series of tests were performed using coal ash, ground coal, and petroleum coke (petcoke) to simulate accelerated testing at gas temperature and velocity of modern first stage high-pressure turbine vanes. Four different sizes of coal ash were used, resulting in deposition rate greater than double as particle mass mean diameter increased from 3µm to 16µm with the presence of thermal barrier coating (TBC) spallation at larger particles size. Deposition threshold gas temperature was found to be at approximately 960°C and particle deposition rate increased as gas temperature increased. Additionally, impingement cooling was used to simulate internal vane cooling. Results showed that capture efficiency for ground coal and petcoke ash particulates decreased with increased mass of coolant air. However, deposits attached more firmly to the TBC layer at low levels of cooling. In 2015, coal flyash and a nickel base superalloy metal coupon were tested at two different test series [28]. The first series conditions consisted of particle temperature varying between 1200°C and 1400°C while maintaining an initial coupon surface temperature of 1000°C. The second series conditions consisted of varying initial coupon surface temperature between 1050°C and 1200°C while maintaining a constant particle temperature at 1400°C. Results from testing indicated that capture efficiency increased as particle temperature increased from 1200°C to 1400°C. On the other hand, as surface temperature increased capture efficiency increased until it reached a certain threshold then it decreased with increasing surface temperature. Subsequent testing was performed in 2017 using heavy fuel oil ash on an uncooled metal coupon with gas temperatures between 1088°C to 1206°C [29]. The results indicated no clear relationship between capture efficiency and gas temperature.

Since 2016, Virginia Tech has been conducting experiments using a flat HX coupon and 20 – 40µm ARD sample to quantify the onset of sand deposition in hot section turbine conditions [13-16]. Unlike previous mass-based deposit studies, the Virginia Tech team used a semi-autonomous image processing method to count individual particle deposit on test coupons. Testing in 2016 examined critical testing variables such as gas temperature and coupon impingement angle. Deposit results from testing showed that coupon impingement angle, ranging from 30° to 90° (increments of 10°), have little to no noticeable trend. As gas temperature increased from 975°C to 1075°C, deposits increased linearly, as expected. The focus of the 2017 tests was on the effect of impact velocity components (normal and tangential) and local surface temperatures. All tests were conducted at 1000°C to 1100°C and a hybrid Particle Image Velocimetry-Computational Fluid Dynamics (PIV-CFD) method was used for particle tracking. Deposits data were used to develop an experimental empirical Coverage Ratio (CR) model to determine deposit accumulation. The model showed that tangential impact velocity has an independent effect on deposits relative to normal impact velocity and local surface temperatures. A complementing numerical model study was performed to develop a Sticking Probability (SP) model [30]. Sticking probability is the ratio of particles that stick to the surface to the number of particles that impact in the same location. Results from the SP model study was in agreement with results from the CR model study.

ARD has also been used for testing on NGV. A concentric cylinder test article was designed in 2016 to represent a simplified representation of the leading edge of an NGV. The article was tested to study the effect of particle loading, size, and temperature on deposition [31]. 0 – 5µm, 0 – 10µm, and 0 – 20µm nominal size distribution ARD were used in uncooled testing conditions at flow temperatures between 427°C to 593°C. Results concluded that particle loading rates had little impact on flow blockage development and particles smaller than 2.66µm were likely to deposit on first impact while larger particles

often rebound. A subsequent study was performed in 2017 using 0 – 10 μ m nominal size distribution ARD to study the effects of metal surface temperature on flow blockage [32]. Flow temperature was kept at a steady 593°C while the external surface temperatures were altered between 647°C and 989°C using an electric kiln. Results from testing indicated blockage development increased with increasing external surface temperature. Figure 4 illustrates the deposits buildup inside the cylinders. In 2016, accelerated deposition testing using ARD was performed to investigate the effect of temperature on external deposition on a cooled CFM56 NGV [33]. Testing was performed at inlet temperatures between 1091°C and 1350°C and cooling temperatures between 382°C and 538°C. Results indicated deposition on the vane pressure surface increased with increased inlet temperatures and a cluster of deposition observed near the trailing edge was due to particle ricocheting off of the leading edge and depositing downstream.

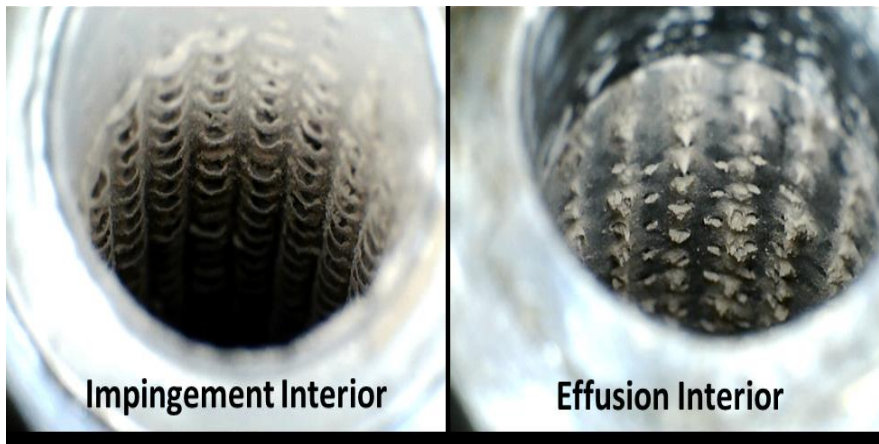


Figure 4: Deposits buildup on the interior of the concentric cylinders [33].

Full-scale and HSTS testing were performed to quantify the operational lifespan of engines and engine components [2,4,22-25]. Full-scale and HSTS testing results explained the interaction between dust, and gas and surface temperatures, but studies examining material interactions with ash and sand were necessary. To study the material interactions with ash and sand, accelerated deposition and erosion testing were performed using ash and ARD on test coupons with various cooling schemes and engine hardware [26-29,31-33]. Accelerated testing provided useful insight into the mechanisms responsible for deposit accumulation but evaluating deposits prior to significant accumulation may provide information for improved engine design. Studies were performed at Virginia Tech to evaluate the initial onset of deposits using uncooled HX coupons and 20 – 40 μ m ARD sample [13-16,30]. Results from testing were used to establish the onset of deposits, which is the base layer of rapid accumulation. As a continuation of previous onset deposition studies, this study used cooled HX coupons to decouple particle and surface temperatures which can provide insight into the response of onset deposits.

EXPERIMENTAL METHOD

The experiments for this study were performed at the Advanced Power and Propulsion Lab at Virginia Tech utilizing the Virginia Tech Aerothermal Rig (VTAR). The following sections describe the test facility, test coupon and particulate used in this study, the conditions at which the tests were performed, and finally how the data were analyzed.

Test Facility

Testing on the internally cooled HX flat plate test coupon was performed using a water-cooled sudden-expansion burner rig donated to Virginia Tech from Rolls-Royce Corporation. Before arriving at Virginia

Tech in 2010, the burner rig was previously used to study heat transfer on cascade turbine airfoils [34-37]. After arriving at Virginia Tech, the burner rig was repurposed to be able to study particle impact and rebound at high temperature test conditions [6-9,11-12] and renamed the Virginia Tech Aerothermal Rig (VTAR). In the last few years, VTAR was used to study microparticle sand sticking probability and coverage ratio of ARD on a solid HX coupon [13-16]. The current iteration of VTAR used for cooled coupon testing consisted of an air valve, a water-cooled propane-fueled sudden-expansion burner, equilibrium tube (EQT), test section, inline air heater, and exhaust system.

Figure 5 illustrates a rendering of the current iteration of VTAR used for sand deposition testing. A mixture of air and propane entered the water-cooled burner, producing hot combustion gases. The combustion gases flow through the EQT where ARD particulates were injected into the EQT via a venturi vacuum pump. The particulates were then mixed and accelerated towards the test section, and ultimately the test coupon. To ensure that the ARD particulates have sufficient time to achieve steady-state conditions, the sand injector nozzle was placed 1.7m from the end of the EQT (test section side). A K-type thermocouple was placed 15.24cm before the sand injector nozzle to measure hot combustion gases temperature exiting the water-cooled burner. The 2m long, 7.62cm inner diameter EQT was fabricated using 310 Sch 40 stainless steel. A water and air-cooled exhaust system, placed at the end of the test section, was used to help expel hot combustion gases produced by the burner.

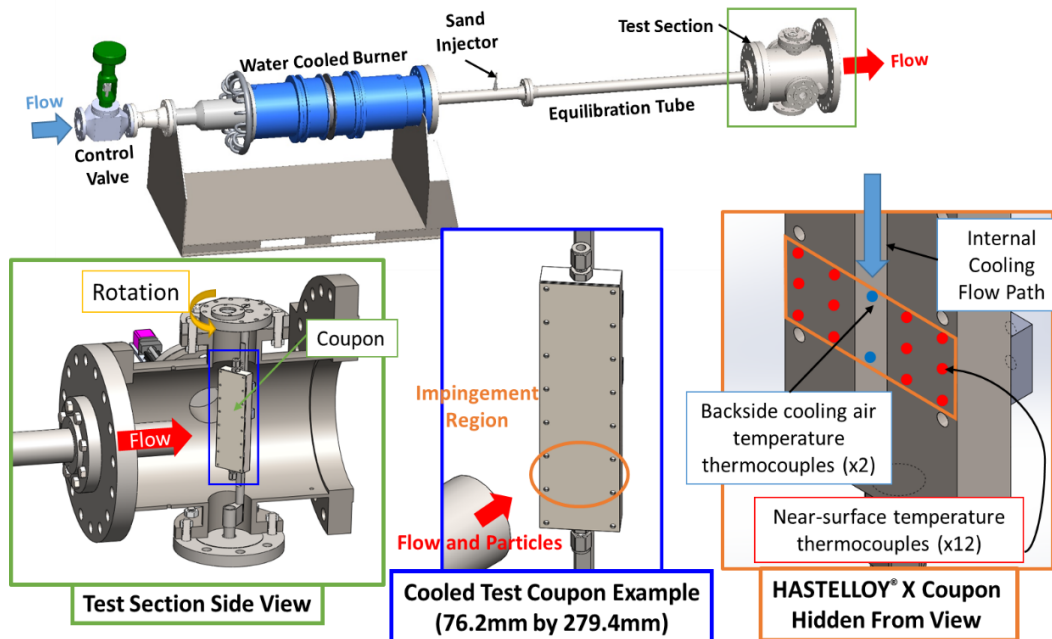


Figure 5: The Virginia Tech Aerothermal Rig utilized for deposition testing, highlighting the test section cut-away view, the associated coupon and thermocouples placement. The coupon impingement region is highlighted in orange.

Test Coupon

The test coupons were fabricated using HX, which is a nickel-chromium-iron molybdenum alloy. Due to its exceptional resistance to oxidation, high-temperature strength, and resistant to stress-corrosion cracking [38], HX can be commonly used to fabricate hot section components [15]. The 27.94cm by 7.62cm by 0.2cm thick test coupon was mounted to a support structure which allowed the coupon to rotate in 10° increments along the vertical axis. This feature allowed the coupon to be parallel to the flow (0°), normal to the flow (90°), or in any 10° increments coupon angle (θ) prior to the start of testing. A top-down view

of the internally cooled test coupon illustrating coupon angle is shown in Figure 6. The coupon angle is the acute angle between the gas path and the surface of the coupon. At a 50° coupon angle, the leading edge of the coupon was approximately 11.05cm away from the end of the EQT in the test section side. Prior to every test, the test coupon's impingement region was polished to a mirror finish to ensure surface roughness effects were minimal. Three K-type thermocouples were used to measure the gas path flow temperature at the impingement region, two at the leading edge (top and bottom) and one at the trailing edge (middle). Twelve addition K-type thermocouples were placed in contact with the back side of the test coupon to measure near-surface coupon temperatures during testing. Finally, two K-type thermocouples were placed within the cooling channel of the coupon support structure, as illustrated in Figure 5. These two thermocouples were used to measure the backside cooling air flow temperatures (T_c) from an 8kW Osram Sylvania inline air heater. The inline air heater was used to alter the near-surface coupon temperatures during testing.

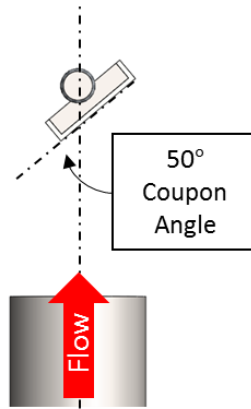


Figure 6: A top-down view of the test section illustrating 50° coupon angle.

Arizona Test Dust

Table 1 summarized the chemical characterization for 20 – 40 μ m ARD from Powder Technology Inc. The primary constituents of ARD are silica and aluminum oxide, which is the same relative International Organization for Standardization (ISO), ISO 12103-01 A2, composition of particles used for particle filtration in automotive and industrial equipment testing. Typically, only particle sizing below 10 μ m will be present after the cold section of the turbine due to larger particles being “pulverized” as they travel through the compressor. A previous study on a TF33 turbofan and J57 turbojet engines showed that the mean particulate sizing after the compressor was approximately 6 μ m [23]. The mechanisms of deposition for particles diameter greater than a few microns are dominated by inertial impaction. Alternatively, turbulent diffusion and thermophoresis dominate the mechanisms of deposition for particles less than a few microns [39]. Although 20 – 40 μ m ARD particle sizing used in this study is not a direct representative of sand sizing in the hot section of gas turbine engines, it can still be considered a reasonable analog for deposition studies. Additionally, 20 – 40 μ m ARD used in this study helps maintain consistent testing parameter similar to previous sand particulate studies performed on VTAR [6-9,11-16].

Table 1: Chemical characterization for Arizona Road Dust from Powder Technology Inc.

Components	Quantity (Percent by Weight)
Silica (SiO_2)	69 – 77%
Aluminum oxide (Al_2O_3)	8 – 14%
Calcium Oxide (CaO)	2.5 – 5.5%
Potassium oxide (K_2O)	2 – 5%
Sodium oxide (Na_2O)	1 – 4%

Iron (III) oxide (Fe_2O_3)	4 – 7%
Magnesium oxide (MgO)	1 – 2%
Titanium dioxide (TiO_2)	0 – 1%

For reference, 20 – 40 μm ARD sample from Powder Technologies Inc. is labeled based on particle size relative to volume distribution. However, a 20 – 40 μm ARD sample has an actual particle size distribution of 2 – 40 μm based on cumulative percentage size distribution. This is illustrated in Figure 7.

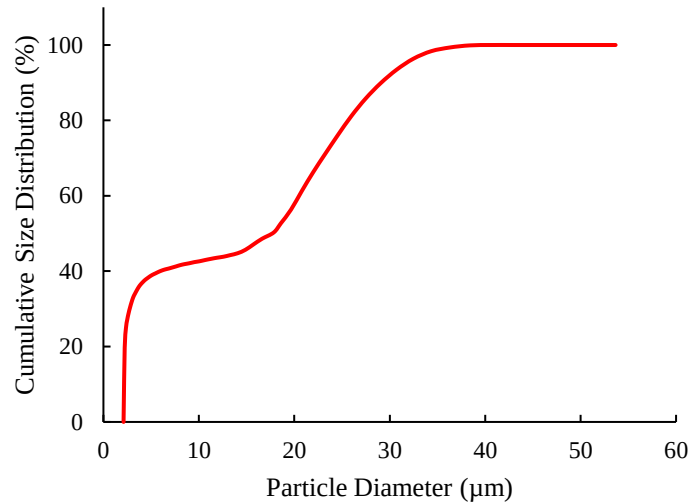


Figure 7: Cumulative particle size distribution based on percent for 20 – 40 μm ARD provided by Powder Technology Inc.

Test Conditions

For the purpose of this study, the test coupon angle was kept constant at 50° for all test cases. Previous studies using a solid HX test coupon have shown that testing at 50° coupon angle resulted in a relatively linear temperature distribution with less than $\pm 5^\circ\text{C}$ variation [15]. The measured flow velocity (V) entering the test section was also kept constant at $70 \pm 2 \text{ m/s}$. This was to maintain consistency testing condition similar to previous sand particulate studies performed on VTAR [6-9,13-16]. Using two K-type thermocouples located at the leading edge and one K-type thermocouple located at the trailing edge, the gas temperatures for this study were measured and they were at approximately 1050°C and 1100°C. The gas temperature criteria were set based on sintering testing of ARD which showed that the critical sintering temperature is approximately 1100°C for particles less than 63 μm [40]. Since this study used 20 – 40 μm ARD particulate, the critical temperature where the particulate will begin to soften and/or sinter was at approximately 975°C to 1075°C [13]. Depending on the desired testing condition, the main gas path mass flow rates were approximately 0.048 to 0.053 kg/s. Additionally, an 8kW inline air heater was used to simulate internal cooling at the middle section (1.4cm wide) of the test coupon support structure, as illustrated in Figure 5. The initial cooling air temperatures ($T_{c,i}$) were set at 250°C or 500°C before the start of testing, depending on the desired cooling condition.

The sand injection system was maintained from the previous Coefficient of Restitution (COR) and deposition studies [11-16]. To help reduce the chances of ARD clumping during testing, 5g of ARD was dried in a high temperature incubator at 150°C for a minimum of 12 hours prior to testing. The dried sand was placed on a conveyor belt inside a sealed box before it was entertained in a flow separate from the main gas flow. The sealed box helps prevent contamination from environmental dust and humidity. A particulate

filter and an air drying system were also used to help equalize the pressure inside the sealed box. Prior to injecting ARD, the leading edge gas path temperatures were maintained within 5°C of the desired testing gas path temperature and the target bulk flow velocity was maintained to within 2m/s of the desired testing velocity. Once all testing parameters achieved steady-state conditions, ARD was then injected. The ARD travels on the conveyor belt to a venturi vacuum pump. A sand scraper was used to ensure the majority of the ARD drops from the conveyor belt and into the vacuum pump. Particle-laden flow then travels to the injector nozzle located on the EQT. The ARD was then delivered to the polished HX test coupon located in the test section. Previous ARD deposition studies show that sand accumulation inside the sand injection system and EQT was insignificant per periodic inspections and mass losses were less than 0.01g from the conveyor into the vacuum venturi pump [15]. Since the vacuum pump disperses the particle from forces induced by the acceleration and shear flow fields, ARD accumulation during testing was minimal [41]. Particulate concentrations can be as high as 5000 parts per million by weight (PPMW) in extreme rotor wash conditions but typical rotor wash was approximately 1000PPMW [42]. To closely match the typical rotor wash condition, 5g of ARD was injected between 82 and 92s per test for an injection rate of 0.055 to 0.061g/s. For all test conditions, the resulting particulate concentrations were approximately between 1090PPMW and 1230PPMW. Table 2 summarized the test conditions for this study.

Table 2: Testing conditions for internally cooled coupon.

Coupon Material	HASTELLOY® X
Coupon Impingement Region	3.81cm x 7.62cm
Coupon Thickness	0.2cm
Coupon Angle	50 deg
Gas Path Temperature	1050 – 1100°C
Gas Path Flow Rate	0.048 – 0.053kg/s
Cooling Air Temperature	250°C, 500°C
Particulate Type/Size	ARD, 20 – 40µm
Particulate Loading	5g
Injection Rate	0.055 – 0.061g/s
Particulate Concentration	1090 – 1230PPMW

To investigate the effect of thermal gradient on particulate deposition, two different of gas temperatures and three different of cooling conditions were investigated. The combination of the two testing conditions led to a total of twelve possible experimental conditions, represented by Table 3.

Table 3: Test matrix for coupon angle, flow velocity, varying cooling air, and gas path temperature. “NC” coolant temperature represents no cooling air flowing through the internal cooling channel.

Tg (°C)	Tc,i (°C)	ARD Loading (g)	θ (deg)	V (m/s)
1050	NC	5	50	70
	500			
	250			
1100	NC			
	500			
	250			

Analysis

Two parameters, near-surface coupon temperatures and particle deposits, were investigated to study the effect of thermal gradient on the onset of deposition on an HX coupon. Near-surface coupon temperatures were analyzed using direct temperature measurements from each experimental testing conditions. Particle

deposits were analyzed using an improved object recognition algorithm to count individual particles across three horizontal rows of the coupon surface.

Near-Surface Coupon Temperatures

There have been extensive studies at Virginia Tech in regards to the interaction of substrate and surface temperatures with particulate deposition. One previous study assumed an isothermal condition where the coupon surface temperature was approximately 140°C lower than the main gas path temperature [12]. Most recently, studies were performed under the assumption that surface temperature is not isothermal and a linear distribution surface temperature profile was present across the horizontal plane of the coupon for 50° coupon angle cases [13-16]. Although coupon surface temperature was not directly measured, a one-dimensional jet impingement onto a flat plate heat transfer calculation was used to estimate the coupon surface temperature. It was determined that the coupon angle has minimal effect on surface temperature and was within $\pm 2^\circ\text{C}$ of the measured near-surface coupon temperature for all cases [13].

Unlike previous studies performed on VTAR, this study used an internal cooling channel to study the effect that thermal gradient has on particle deposition. An 8kW Osram Sylvania inline air heater was used to cool the coupon during testing. Three different cooling cases were investigated at no cooling, 500°C cooling, and 250°C cooling conditions. In order to get the precise cooling condition, a K-type thermocouple was placed directly after the air heater and the heater was controlled by an ATHENA Series 16C temperature controller. The cooling conditions were set before the start of each test and is at the target cooling temperature once the testing starts. Two addition K-type thermocouples were placed inside the coupon cooling channel to record the cooling air temperatures. The cooling air temperatures will be used to estimate the near-surface coupon temperature at the cooling region. Twelve additional K-type thermocouples were placed on the back of the testing coupon to measure near-surface coupon temperatures during testing. Figure 8 illustrates the placement of fourteen K-type thermocouples in the coupon impingement region plus three additional K-type thermocouples used to measure main path gas flow.

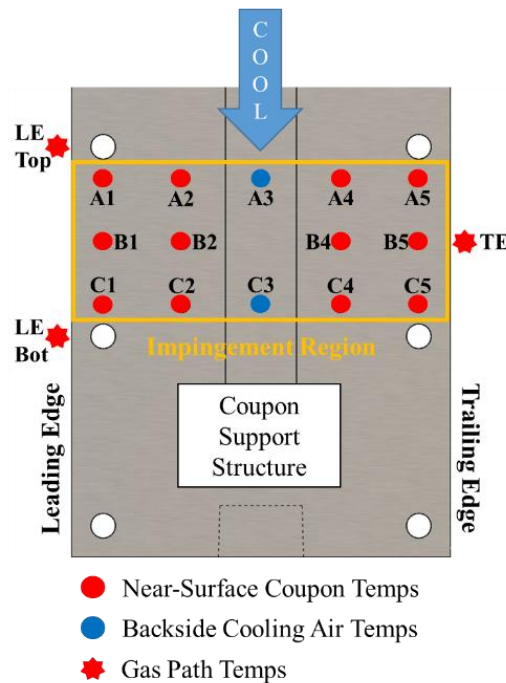


Figure 8: 17 K-type thermocouples used to acquire steady-state temperatures during testing. The thermocouples were labeled according to their relative location on the coupon support structure.

Data Reduction for Particle Deposits

An improved object recognition algorithm developed at Virginia Tech was used to identify individual particles based on color [13-16]. Post-test coupon images were manually acquired using a Zeiss Axio Vert.A1 with an AxioCam MRc5 digital microscope at 20x magnification with an image size equivalent to $698\mu\text{m}$ by $522\mu\text{m}$. Images were taken across the coupon, in the horizontal direction, starting from the coupon leading edge to the trailing edge. Since manual manipulation was required with the acquiring of images, relatively equal spacing between each image was assumed. Each test coupon produced between 60 and 80 images per sample row. Three sample image rows validated equal vertical deposit exposure. Figure 9 highlights the relative location of each image sample row along with microscopic images of the test coupon pre-test and post-test.

A detailed description of the image processing algorithm was described in a previous study performed at Virginia Tech [15]. Each image was acquired with the focus set to the HX substrate. This caused the particle deposits to be slightly out of the focal plane of the microscope. As a result, a relative boundary between the ARD deposits and the surface pattern was formed. Functions from MATLAB® Image Processing Toolbox were then used to process each image by examining the pattern, texture, and color gradient differences between the carburized HX surface and deposits. All images were then converted from color model to grayscale. The gradient of the grayscale images in combination with a Gaussian blurring effect was used to identify areas with low variation. Those areas were typically “blurred” in the original image due to the deposit being out of the focal plane. Blurred gradient images were then converted to black and white and then an automatic selection function identified the potential particles. Particle deposits larger than $10\mu\text{m}$ in equivalent diameter were automatically selected for each image while particle deposits less than $10\mu\text{m}$ in equivalent diameter were infrequent and therefore disregarded. Each image was manually validated and manipulated to add or remove deposits.

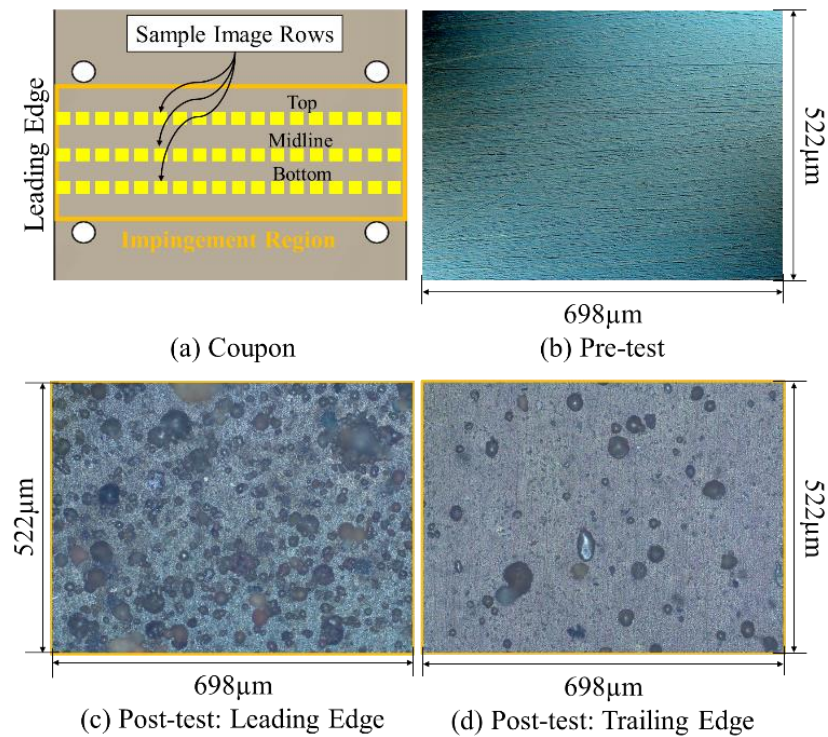
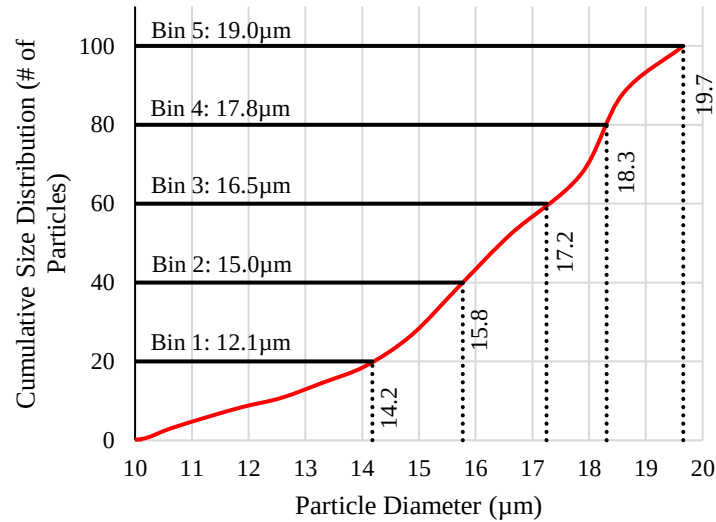


Figure 9: Rendering image of coupon impingement region along with pre-test and post-test surface sample images comparison showing the deposits at 20x magnification. Images (c) and (d) were from a 500°C cooling test condition.

A study performed using VTAR aimed to develop a SP model using experimental deposits testing results. SP was statistically quantified using 20 – 40 μm ARD sample and at gas temperatures between 1000°C and 1100°C [16]. Using the cumulative particle size distribution data provided by Powder Technology Inc., 20 – 40 μm ARD was separated into normalized particle bin size distribution normalized based on number of particles between 10 μm and 40 μm . Deposits of particles less than 10 μm were infrequent and therefore negligible. The smallest particle bin size, 10 – 19 μm , was found to have a predicted SP approximately five times greater than the larger particle bin sizes. Based on this finding [16], the analysis for this study will only focus on the particles that range in equivalent diameters of 10 – 19.7 μm . Figure 10 shows the five bins of sand sizes and their respective nominal diameter used for deposition analysis. Each bin has an equal number of particles for a given sample of ARD. Equal size bins based on the number of particles were used to directly compare the total number of deposits at the midline row with a nominal particle size.



Nominal Diameter				
Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
12.1 μm	15.0 μm	16.5 μm	17.8 μm	19.0 μm

Figure 10: Normalized particle size distribution based on number of particles that has been normalized between 10 μm and 19.7 μm for 20 – 40 μm ARD sample. The particle size distribution was broken down into five different bin sizing and their respective nominal diameter.

RESULTS

Experimental internally cooled coupon tests were conducted at twelve different test conditions to analyze the effect of near-surface coupon temperatures on the onset of microparticle deposits of turbine components at near gas turbine hot section temperatures, at 50° impact angle. The experimental results were broken into two sections: near-surface coupon temperatures and particle deposits.

Near-Surface Coupon Temperatures

For this study, a linear temperature gradient across the coupon can no longer be assumed valid for test conditions with internal cooling air. Although an in-depth heat transfer analysis was not performed for this study, fourteen K-type thermocouples temperature measurements were used to provide a range of near-

surface coupon temperature at the cooling channel section of the test coupon. Table 4 summarized the twelve test cases that were performed for this study. Testing indices were grouped into their respective testing conditions of no coolant, 500°C coolant and 250°C coolant, respectively. Although three K-type thermocouples were used to measure primary gas flow temperatures, the highest temperature measurement was used to represent the testing gas flow temperature (Tg). The remaining fourteen thermocouples were labeled according to their relative locations on the test coupon support structure, as shown in Figure 9. Thermocouples A3 and C3 were used to measure the backside cooling air temperature (Tc) inside the cooling channel during testing, and were not taken into consideration when averaging the near-surface coupon temperature (Ts) for each tests.

Near-surface coupon temperature is a function of primary gas path temperature and cooling air conditions. Figure 11 illustrates the relationship between average surface temperature, gas flow temperature, and internally cooling conditions. Average surface temperature increased with increasing gas temperature, as expected. Closer examination of temperature results also reveals that the cooling air conditions affect the overall near-surface coupon temperature, similar to internal vane cooling that is widely used in the gas turbine industry. Test cases with no cooling have the highest overall average near-surface coupon temperature and test cases with 250°C cooling will have the lowest overall average near-coupon surface temperature.

Table 4: Primary gas path flow, and average surface and leading edge (LE) temperatures for twelve test cases during ARD injection.

Thermocouple	Testing Index (Tc,i: NC)				Testing Index (Tc,i: 500°C)				Testing Index (Tc,i: 250°C)			
	1	2	3	4	5	6	7	8	9	10	11	12
Tg	1041	1048	1088	1097	1049	1074	1096	1091	1085	1090	1078	1120
A1	879	916	940	940	871	866	904	889	871	877	862	882
A2	878	927	926	930	827	850	896	855	846	858	860	806
A3	806	857	892	859	496	524	565	537	433	435	429	438
A4	788	840	877	845	726	763	808	785	757	759	751	776
A5	780	828	869	849	732	766	809	786	775	769	754	788
B1	862	909	935	923	836	849	896	874	865	866	852	872
B2	845	882	921	909	794	825	866	842	830	772	813	811
B4	791	842	880	857	732	766	811	780	762	766	746	769
B5	778	831	870	853	727	769	813	793	771	834	759	791
C1	857	923	940	919	844	867	889	879	862	883	851	885
C2	840	879	919	903	791	824	863	831	825	825	813	816
C3	810	862	897	859	504	529	563	537	439	439	427	435
C4	790	843	877	889	723	765	813	812	757	769	760	804
C5	771	829	870	841	716	768	812	786	768	770	770	780
Avg Ts	822	871	902	888	777	807	848	826	807	812	799	815
Avg LE	866	916	938	927	850	861	896	881	866	875	855	880

For testing conditions where no internal cooling scheme was applied, a relatively linear temperature gradient profile was present. Surface temperature gradient decrease from the coupon leading edge to the trailing edge, as expected. However, a non-linear temperature gradient profile was present for testing conditions where internal cooling scheme was applied to the testing conditions. For testing conditions with initial cooling air temperature of 500°C and 250°C, the cooling air inside the coolant channel ranged from 496 – 565°C and 429 – 439°C, respectively. This was due to conduction heat transfer from the coupon support mount and convection heat transfer from the primary gas path flow and cooling air flow in the cooling channel. Figure 12 illustrates the contour plots for three test cases at constant gas path temperatures but three different cooling testing conditions. The red and blue markers represent thermocouples and their relative locations on the test support structure and the dashed lines represent the cooling channel region of

the test coupon, as shown in Figure 5 and Figure 8. Due to the 500°C and 250°C cooling schemes, the near-surface coupon temperatures at the cooling channel region (highlighted by the black dashed lines) were the lowest near-surface temperatures for each respective test cases. Near-surface coupon temperatures were the highest at the leading edge and gradually decrease until after the cooling channel section where near-surface temperatures slightly increased.

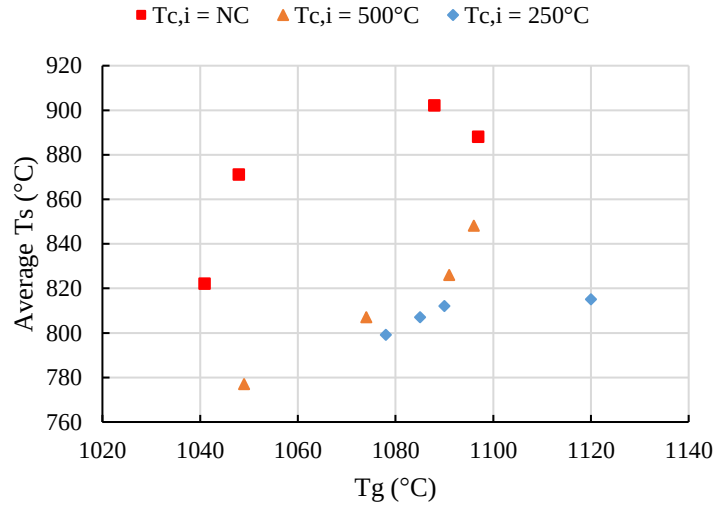


Figure 11: A comparison of average surface temperature versus achieved gas temperature for twelve test cases.

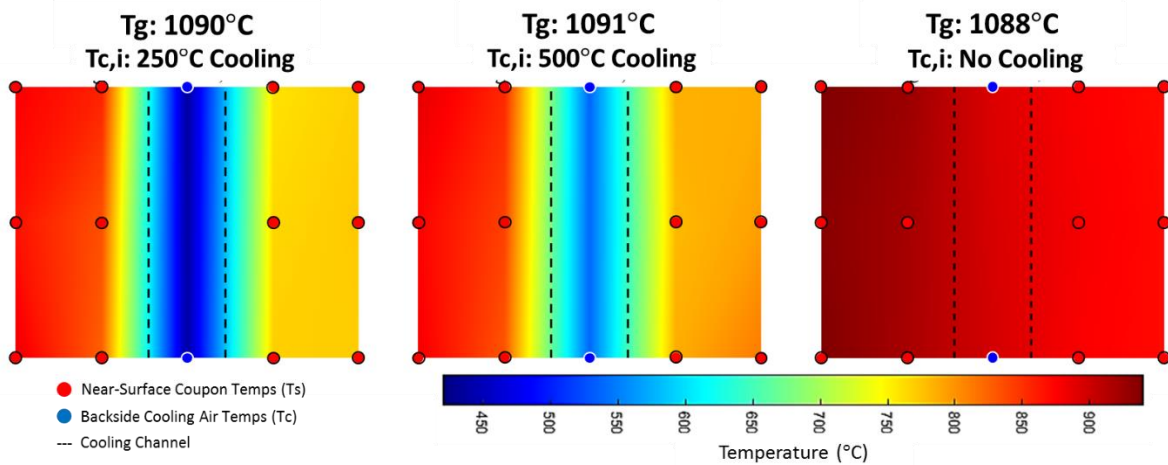


Figure 12: Contour plots of near-surface coupon and backside cooling air temperatures across the coupon impingement region during ARD injection. Dash lines represent the cooling channel.

Particle Deposits

Based on previous studies performed on VTAR and the testing conditions for this study, particles on the coupon surface do not appear to have delaminated during or after the post-test cool down stage. This could be due to the local adhesion between the HX substrate and SiO₂, a nickel-based alloy and a primary constituent for ARD, respectively. The local adhesion created a strong bond that was resistant to thermal

cycling. A previous study concluded that a crystalline SiO_2 layer between a nickel substrate alloy and a TBC layer could provide the bond strength necessary to avoid delamination during thermal cycling [43].

Figure 13 (a) is an original microscopic image of the test coupon post-test and Figure 13(b) is a cropped version of Figure 13(a) microscopic image. Using MATLAB® Visual Processing Toolbox, particulates were automatically identified and selected. Each image was then manually checked to ensure all particles between $10\mu\text{m}$ and $19.7\mu\text{m}$ were identified and selected, as illustrated in Figure 13(c). Post-test microscopic images reaffirm that there was no evidence of particles delamination on the coupon surface.

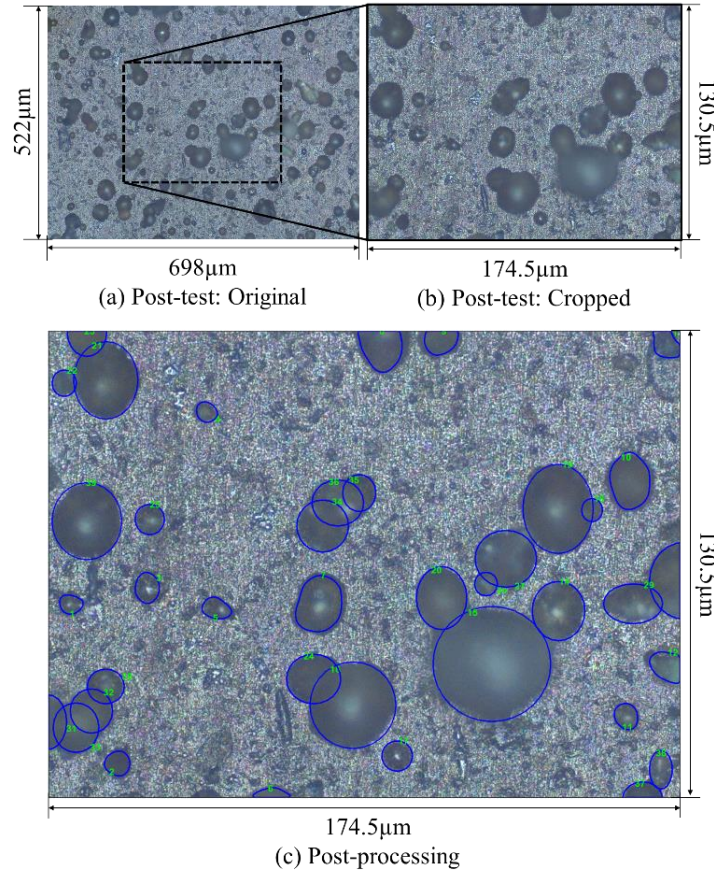
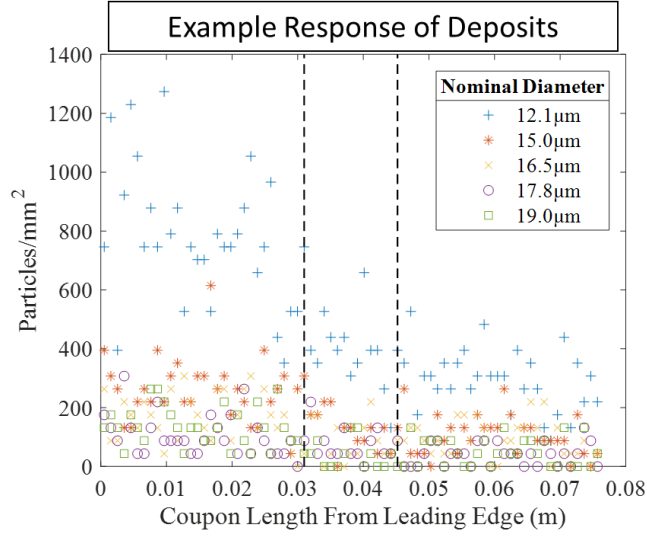
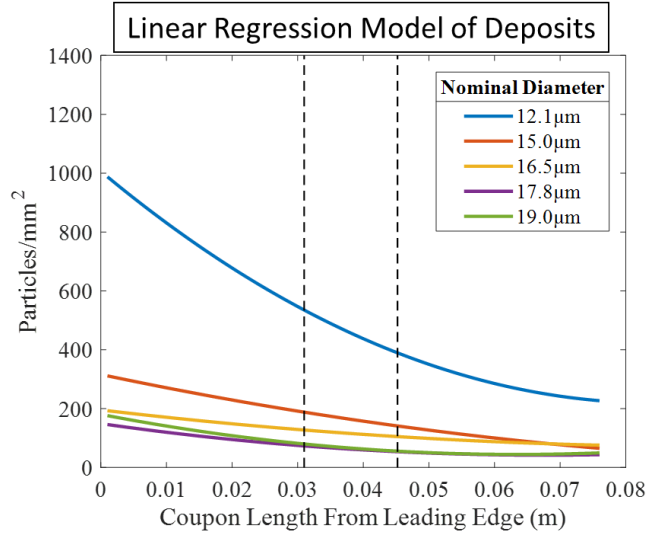


Figure 13: Post-test and post-processing images of particulate deposition. (a) Post-test microscopic image at 20x magnification with an original image size equivalent to $698\mu\text{m}$ by $522\mu\text{m}$. (b) Post-test microscopic image at 20x magnification with a cropped image size equivalent to $174.5\mu\text{m}$ by $130.5\mu\text{m}$. (c) Post-processing microscopic image with particulates automatically and manually selected. All images were from a 500°C cooling test condition.

Once each image was processed and particles were identified, the total number of deposits per image was separated into five bins based on nominal diameter. Deposits across the test coupon were then quantified based on location and particle sizing. Figure 14(a) is an example response of raw data deposits for one test case. Each microscopic images contain five markers, each representing their respective bin sizing. Figure 14(a) illustrates an example response of raw deposits data for one test case. From the raw data, a linear regression model was used to establish a trend for the five bin sizes. Figure 14(b) illustrates a linear regression model of deposits within the impingement region. From the linear regression model of deposits, it was concluded that smaller particles deposits, $10 - 14.2\text{m}$, were more prominent across all tests.



(a) Raw deposit data



(b) Linear regression model

Figure 14: Response of deposits across the impingement region. Dash lines represent the cooling channel. (a) Response with raw deposit data and (b) Linear regression model from raw deposit data.

Three test cases at constant gas path temperature of 1090°C were used to study the sensitivity of ARD deposits to cooling conditions. Since smaller particles deposits, 10 – 14.2µm were more prominent, this analysis only examined deposits with nominal diameter of 12.1µm. Figure 15 illustrates a linear regression model response of deposits across the impingement region for three test cases at three cooling testing conditions of no cooling, 500°C cooling, and 250°C cooling.

As backside cooling air temperature decreased, deposits at the leading edge decreased. This is in agreement with previous accelerated testing using ash and test coupons with backside cooling conditions [27,28]. However, towards the cooling channel and the trailing edge, there was evidence of deposits increasing as backside cooling air temperature decreases. These trends are in agreement with the accelerated study using ash and test coupons with backside cooling conditions [28]. One explanation for this unexpected

trend could be due to a possible transition point where deposit viscosity becomes too low, therefore decreasing the particle stickiness. Other accelerated studies, using ARD and cylinders to represent the leading edge of an NGV [31] and actual NGV hardware [33], showed that particles that did not deposit at the leading edge will more likely rebound on first impact and deposit downstream. This would be evident with the 250°C cooling testing condition. Overall, the effects of cooled surfaces with ARD particles of 10 – 14.2µm size have a small impact on deposit formation.

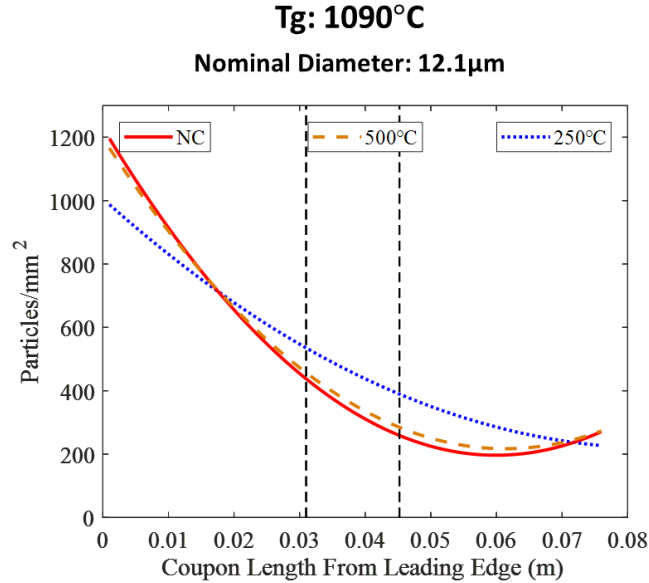


Figure 15: Linear regression model response of deposits across the impingement region for three cooling testing conditions. Dash lines represent the cooling channel.

CONCLUSIONS

Experimental testing was conducted at the Advanced Propulsion and Power Lab located at Virginia Tech to study the onset of Arizona Road Dust deposits. Results from this study can provide useful insight into the onset of particulate deposits, which is the base layer of rapid accumulation. Experiments were performed in high temperature environments using flat HASTELLOY® X coupons and 20 – 40µm Arizona Road Dust particulate. Gas path temperatures were varied from 1050°C to 1100°C and cooling testing conditions consisted of no cooling, 500°C cooling, and 250°C cooling. Testing bulk velocity and impact angle were kept at a constant 70 m/s and 50°, respectively. The following inferences are concluded from this study:

- 20 – 40µm Arizona Road Dust sample contains actual particle size distribution of 2µm to 40µm. By analyzing cumulative size distribution between 10µm and 19.7µm, particle deposits for Arizona Road Dust between 10µm and 14.2µm were more prominent in all test cases.
- Internally cooled testing conditions affect steady-state near-surface coupon temperatures, similar to internal vane cooling that are widely used in the gas turbine industry. Thermal gradients were found to be between 200°C and 300°C, depending on testing conditions.
- Linear regression model response of deposits across test coupons at constant gas path temperature indicated that the cooling testing conditions of 500°C and 250°C used in this study may not have a first-order effect on particle deposition.

Future research plans include:

- Conjugate heat transfer analysis to better quantify near-surface temperatures at coupon cooling channel.
- Based on results from cooled coupon experiments, examining deposits trends are particles less than 10 μ m in nominal diameter will provide a better understanding of particle impacts and rebounds.

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Appendix A: Particle Deposition Data Reduction Code

New image processing codes were developed to improve the accuracy and speed of particle identification. First, the **ImageCropV1R0** code was used to cropped each microscopic images to a fourth of the size of the original microscopic image. Next, the **run_script_v18_rev7** code was used to calibrate each images using various filtering and sizing of particles. Images were converted to grayscale and a gradient filter was applied. The gradient filter increased the contrast of each image and a Gaussian blur was applied to help identify shaded regions which were potential ARD particles. Particles larger than 10 μ m were automatically selected and filtered according to their sizes. Particles that were not automatically selected were then manually selected to ensure all ARD particle deposits were accounted for. Finally, **DataReduc_03_Cool** code was used to merge particle deposit files for a single test case into one single file.

ImageCropV1R0

```
func_fldr = uigetdir('', 'SELECT IMAGE CROPPING PROGRAM FOLDER');
img_fldr = uigetdir('', 'SELECT TEST IMAGES FOLDER');
img_fldr = [img_fldr '\'];

% change the working folder directory
cd(img_fldr)
addpath(func_fldr);

% create new folder with cropped images
mkdir('Cropped');

% create an array of the meta data from the jpeg and bitmap images
meta = [dir('RAW\*.jpg'); dir('RAW\*.bmp'); dir('RAW\*.png')];
% find the total number of pictures of the specified formats
num_pics = size(meta,1);

% CROP EACH IMAGE TO 1/4TH THE ORIGINAL PIXEL SIZE
i = 1; a = 1;
while a == 1
    %close all previously opened images
    close all;
    % Print the image index in the workspace that is currently being
    % used
    fprintf('Index: %i ,Image: %s \n', i, meta(i).name);

    % Grab the image file
    filename = [img_fldr '\RAW\' meta(i).name];

    % Crop the image and save it as a new version
    I = imread(filename);
    % Find pixel center of the image
    Ox = round(size(I,2)/2);
    Oy = round(size(I,1)/2);
    % find the new cropped image x and y half lengths
    Lx = round(size(I,2)/4);
    Ly = round(size(I,1)/4);
    % Crop middle of image
    I2 = imcrop(I, [Ox-Lx Oy-Ly 2*Lx 2*Ly]);% [xmin ymin width height]
    % save new image to cropped folder
    imwrite(I2,[img_fldr 'Cropped\' meta(i).name(1:end-4) '_crop.png'])
```

```

        % Break the loop if you get to the end of the data set
        if i == num_pics
            break; % stop the loop
        else
            % iterate to the next image index
            i = i + 1;
        end
    end

end

run_script_v18_rev7

func_fldr = pwd;
img_fldr = uigetdir('', 'SELECT TEST IMAGES FOLDER');
img_fldr = [img_fldr '\'];

% change the working folder directory
cd(img_fldr)

addpath(func_fldr);

%% Filtering and Sizing of Particle presets

% particle sizes
sizes.scale = 0.27; % microns per pixel for this data set
sizes.Min = round(20/sizes.scale); %pixels 20 um = 74 pixels @ 20x
magnification
sizes.Max = round(40/sizes.scale); %pixels 40 um = 148 pixels @ 20x
magnification
sizes.MinArea = (pi()/4)*sizes.Min.^2; % in pixels
sizes.MaxArea = (pi()/4)*sizes.Max.^2; % in pixels

% *** HEART OF IMAGE PROCESSING ****
% image filter inputs
filter.alpha = 1; % contrast increasing ratio (adapthisteq func)
filter.gauss = [5 5]; % blurring of the gradient grayscale image
filter.thresh = 0.75; % black/white thresholding
filter.MinArea = round(0.25*floor(sizes.MinArea)); % 10 µm diameter
filter.MaxArea = round(ceil(sizes.MaxArea)); % 40 µm diameter
filter.smooth = [9 9]; % BW low pass median filter
filter.roundness = 0.1;
% *****

% Program mode ("calibrate" or "run")
mode = 'calibrate'; cal_img = 35; % Test image index
% mode = 'run';

% create an array of the meta data from the jpeg and bitmap images
meta = [dir('*.jpg'); dir('*.bmp'); dir('*.png')];
% find the total number of pictures of the specified formats
num_pics = size(meta,1);

%% Analyze all image data

if strcmp(mode, 'run')

```

```

    ImgInd = inputdlg('Enter starting image index (single number only):',...
        'Starting Image', 1, {'1'}); % set default starting point to the
first image

    i = str2double(ImgInd{1}); % specify what image index to start at
    LoopCntrl = 'Continue'; % to start loop for string compare func.
    while strcmp(LoopCntrl, 'Continue')
        %close all previously opened images
        close all;
        % Print the image index in the workspace that is currently being
        % used
        fprintf('Index: %i ,Image: %s \n', i, meta(i).name);

        % Grab the image file
        filename = [img_fldr meta(i).name];
        % particle counting function
        [image(i), statistics(i)] = Particle_Counter_v18_rev2(filename,
filter);

        % create an structure that lists the filename, number of particles,
and
        % particle area
        full_data{i,1} = meta(i).name;
        full_data{i,2} = num2str(statistics(i).num_part);
        full_data{i,3} = num2str(statistics(i).tot_area);

        % Break the loop if you get to the end of the data set
        if i == num_pics
            i = i + 1;
            break; % stop the loop
        else
            % iterate to the next image index
            i = i + 1;
        end

        % Autosave workspace
        autoSaveWorkspace = ['AUTOSAVE_WORKSPACE.mat'];
        save(autoSaveWorkspace, 'filter', 'full_data', 'meta', 'statistics',
'sizes');

        % check if you want to continue to the next loop
        LoopCntrl = questdlg('Continue to next image OR Save and Quit?',...
            'Continue?',...
            'Continue','Save and Quit','Continue');
    end

    % save the workspace data to the file for future processing if necessary
    save_filename = ['workspace_Ind-' int2str(str2double(ImgInd{1})) 'to'
int2str(i-1)...
        '_' datestr(now,'yyyy-mm-dd') '.mat'];
    save(save_filename, 'filter','full_data','meta','statistics', 'sizes');

    % write all image data to text file to copy into the permanent analysis
    % file
    T = cell2table(full_data, 'VariableNames',
{'Image','Particles','Pixels'});

```

```

        save_filename = ['ImageData_Ind-' int2str(str2double(ImgInd{1})) 'to'
int2str(i-1) ...
        '_' datestr(now,'yyyy-mm-dd') '.txt'];
        writetable(T,save_filename);

        close all;

end

%% Preprocessing to determine relative optimal filtering
% keep this section commented while running the main code above
% use this section to get the proper scaling factors

if strcmp(mode, 'calibrate')

    filename = [img_fldr meta(cal_img).name];
    [image, statistics] = Particle_Counter_v18_rev2(filename, filter);

    % montage of all the images from the filters
    % figure; m1 = montage([image.org image.txt]);
    figure; m2 = montage([image.gray1 image.gmag;...
        image.gray2 image.blur]);
    figure; m3 = montage([image.bw1 image.bw2 image.bw3]);

    % figure; imhist(image.blur); title('Blurred Grayscale Histogram');

    save_filename = ['calibration_' datestr(now,'yyyy-mm-dd-HH-MM') '.mat'];
    save(save_filename, 'filter','statistics','sizes');

end

```

DataReduc_03_Cool

```

prompt = {'Test Date (MMDD)' ... %1
        'Test Flow Temperature (°C)' ... %2
        'Coolant Temperature (°C)'... %3
        'Coupon Angle (°)' ... %4
        'Coupon Width (inches)', ... %5
        'Acquired image WIDTHS (pixels)', ... %6
        'Acquired image HEIGHTS (pixels)', ... %7
        'Image Scale (µm/pixel)'}; %8
dlgtitle = 'Test Conditions for file selection';
num_lines = 1;
defaultans = {'' ... %1
        '' ... %2
        '' ... %3
        '50' ... %4
        '3.0', ... %4
        '1293', ... %5
        '969', ... %6
        '0.27'}; %7
x = inputdlg(prompt,dlgtitle,num_lines,defaultans); % save files as a cell
array
TestDate = x{1}; % keep cell array as characters
Input = str2double(x);

```

```

clear x num_lines prompt dlgtitle defaultans

% Test Conditions
T = Input(2); % Test temp in C
CoolTemp = Input(3); % Coolant temp in C
CoupAngle = Input(4); % in degrees

% Coupon width
CoupWidth = Input(5); % inches
CoupWidth = CoupWidth*0.0254; % meters

% Pixels per image
PicImgInfo.PxlTotal = Input(6).*Input(7); %total pixels per image

% micro-meters per pixel
PicImgInfo.um_pxl = Input(8);
% meters per pixel
PicImgInfo.m_pxl = PicImgInfo.um_pxl/(10.^6);
% millimeters per pixel
PicImgInfo.mm_pxl = PicImgInfo.um_pxl/(10.^3);

% Image area
PicImgInfo.mm2 = PicImgInfo.PxlTotal.*(PicImgInfo.mm_pxl.^2); % mm^2
PicImgInfo.um2 = PicImgInfo.PxlTotal.*(PicImgInfo.um_pxl.^2); % μm^2

clear Input

%% IMPORT AND MODIFY WORKSPACE FILES
% import all 3 sample image rows from the test coupon

% Convert data from structures to tables
name = {'Top'; 'Midline'; 'Bottom'};

for i = 1:length(name)

    % preallocate variables
    Deposit.(name{i}) = table;

    [FileName, PathName, FilterIndex] = uigetfile( ...
        {'workspace*.mat'}, ...
        ['Pick all the workspaces from the ' name{i} ' sample image row'],
        ...
        'MultiSelect', 'on');
    addpath(PathName);
    for j = 1:size(FileName,2)
        % Load all workspace files
        Temp(j) = load(FileName{j});

        % Find the different workspace lengths
        L1 = length([Temp(j).statistics.num_part]); % length of imported data
        that exists
        start = length(Temp(j).statistics) -
length([Temp(j).statistics.num_part]) + 1; % start index
        finish = start+L1-1;

        % Metadata
        TempMeta = Temp(j).meta(start:finish);
    end
end

```

```

% Filter data preprocessing
Filter(start:finish) = Temp(j).filter;
% Statistics data
TempStat = Temp(j).statistics(start:finish);

% Horizontally concatenate
TempTable = [struct2table(TempMeta) ...
    table(Filter(start:finish)') ...
    struct2table(TempStat,'AsArray',1)];

% Vertically concatenate
Deposit.(name{i}) = [Deposit.(name{i}); TempTable];

end
clear j L1 start finish TempMeta Filter TempStat
clear Filename Temp TempTable TempStat Filter

% Remove excess variables
% list the variables you want to keep
Deposit.(name{i}) = Deposit.(name{i})(:,{'name', 'Var1', ...
    'num_part','part_area','part_loc','part_bound','tot_area'});
% Change variable names
Deposit.(name{i}).Properties.VariableNames = {...
    'Image', ...
    'Filters', ...
    'PTCL', ...
    'PTCL_Areas', ...
    'Centroid', ...
    'PTCL_Bounds', ...
    'TotalCovA'};
% Change variable units
Deposit.(name{i}).Properties.VariableUnits = {...
    '', ...
    '', ...
    'Particles', ...
    'Pixel', ...
    'Pixel', ...
    'Pixel', ...
    'Pixel'};
% Add variable descriptions
Deposit.(name{i}).Properties.VariableDescriptions = {...
    'Image Name', ...
    'Image Processing Filters', ...
    '', ...
    'Individual particle coverage area', ...
    'XY Location', ...
    'XY Bounds', ...
    'Particle coverage pixel area'};

end

%% REMOVE REPEATED IMAGE DATA

for i = 1:length(name) % each sample image row

    % Remove replicated image data by the share drive system
    loop = 1; j = 1;
    while loop ~= 0 % each image in the same image row

```

```

    % check for image existence
    if j > height(Deposit.(name{i})); break; end

    k = strfind(Deposit.(name{i}).Image(j), '.');
    % keep counting through the rows until the end
    if isempty(k{1}) == 1; j = j+1; end % continue loop

    if isempty(k{1}) == 0
        Deposit.(name{i})(j,:) = []; % remove entry
        j = 1; % reset counter, start loop over
    end

end

% Remove accidental duplicated data by user
loop = 1; j = 1;
while loop~= 0
    % check for image existence
    if j > height(Deposit.(name{i})); break; end

    k = strcmp(Deposit.(name{i}).Image(j), Deposit.(name{i}).Image(:));

    % sum of the logicals
    if sum(k) <= 1; j = j+1; end % continue counting

    if sum(k) > 1 % find repeats
        Deposit.(name{i})(j,:) = []; % remove repeated entry
        j = 1; % reset counter
    end

end

end

% Import the csv files with particle sizes
[FileName, PathName] = uigetfile(['*.csv'], ...
    ['Select the particle size bin file']);
addpath(PathName);
TempDeposit = load(FileName);
BinSeparations = TempDeposit;

clear loop i j k TempDeposit

%% DATA CALCULATIONS

for i = 1:length(name) % image sample row

    % *** Image Index ***
    % number the images
    Deposit.(name{i}).Index = (1:1:length(Deposit.(name{i}).Image))';
    % reorder the variables so the index is first
    varnames = Deposit.(name{i}).Properties.VariableNames;
    others = ~strcmp('Index',varnames); % logical array
    varnames = ['Index' varnames(others)]; %concatenate in correct order
    Deposit.(name{i}) = Deposit.(name{i})(:,:varnames);

    % *** Position ***
    % Location of the image relative to the width of the coupon

```

```

Deposit.(name{i}).Location = CoupWidth*(Deposit.(name{i}).Index-
0.5)/length(Deposit.(name{i}).Index);
Deposit.(name{i}).Properties.VariableUnits(end) = {'meters'}; % set units
Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
    {'Relative image location'};

% *** Coverage Ratio ***
Deposit.(name{i}).CR =
(Deposit.(name{i}).TotalCovA)./PicImgInfo.PxlTotal;
Deposit.(name{i}).Properties.VariableUnits(end) = {''}; % set units
Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
    {'Ratio of area coverage'};

% *** Particles per mm2 ***
Deposit.(name{i}).PTCL_mm2 = Deposit.(name{i}).PTCL/PicImgInfo.mm2;
%particles/mm2
Deposit.(name{i}).Properties.VariableUnits(end) = {'PTCL/mm2'};
Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
    {'Particles per area'};

% *** Particle Area in  $\mu\text{m}^2$  and Equivalent diameter ***
for j = 1:length(Deposit.(name{i}).PTCL_Areas) % total number of images
    % square micron area
    Deposit.(name{i}).PTCL_AreaMicron2{j} = ...
        Deposit.(name{i}).PTCL_Areas{j}*(PicImgInfo.um_pxl.^2);
    % equivalent diameter
    Deposit.(name{i}).PTCL_EqDiaMicron{j} = ...
        2.*sqrt(Deposit.(name{i}).PTCL_AreaMicron2{j}/pi());

    Deposit.(name{i}).Properties.VariableUnits(end-1:end) = {' $\mu\text{m}^2$ ',
'μm'};
    Deposit.(name{i}).Properties.VariableDescriptions(end-1:end) = ...
        {'Coverage area of each particle', 'Equivalent particle
diameter'};
end

% *** Tallies based on bin size ***
for j = 1:length(Deposit.(name{i}).PTCL_Areas) % number of images
    % For each Bin size
    for k = 1:length(BinSeparations)+1
        % Bin naming (Bin_0, Bin_1, etc.)
        BinName{k} = ['Bin_' num2str(k-1)];

        % Lowest bin (less than 10 um, for outliers)
        if k == 1
            Deposit.(name{i}).(BinName{k}){j} = ...

sum(Deposit.(name{i}).PTCL_EqDiaMicron{j}<BinSeparations(k));

            Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
                {'less than ' num2str(BinSeparations(k)) ' μm'};
        end

% Everything else
if k > 1 && k < (length(BinSeparations)+1)
    % Find the number of particles less than the upper bound
    % and less than the lower bound, find the difference to get

```

```

        % a total of particles within the appropriate bin
        Lower =
sum(Deposit.(name{i}).PTCL_EqDiaMicron{j}<BinSeparations(k-1));
        Upper =
sum(Deposit.(name{i}).PTCL_EqDiaMicron{j}<BinSeparations(k));
        Deposit.(name{i}).(BinName{k}){j} = Upper-Lower;

        Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
            {[num2str(BinSeparations(k-1)) ' to '
num2str(BinSeparations(k)) '  $\mu\text{m}$ ']};
    end

    % Highest bin (overlapped particles)
    if k == length(BinSeparations)+1
        Deposit.(name{i}).(BinName{k}){j} = ...

sum(Deposit.(name{i}).PTCL_EqDiaMicron{j}>BinSeparations(k-1));

        Deposit.(name{i}).Properties.VariableDescriptions(end) = ...
            [['greater than ' num2str(BinSeparations(k-1)) '  $\mu\text{m}$ ']];
    end

end

end

% Reformat the Bin Data
for k = 1:length(BinSeparations)+1
    % Bin naming (Bin_0, Bin_1, etc.)
    BinName{k} = ['Bin_' num2str(k-1)];
    % Reformat Bin data type from separate cells to array
    Deposit.(name{i}).(BinName{k}) =
[Deposit.(name{i}).(BinName{k}){:}];
end

end

clear varnames others i j Lower Upper BinName k

clear FileName PathName name

%% SAVE WORKSPACE

SaveFilename = ['DepositData_' num2str(T) 'C' num2str(CoupAngle) 'deg_' ...
    num2str(TestDate) '_' datestr(now,30) '.mat'];
uisave(who, SaveFilename);

```

Appendix B: Inline Air Heater Mass Flow Meter

A code was used to calculate the mass flow rate of the cooling air from the inline air heater using an orifice plate flow meter. Voltage measurements from the flow meter were converted to pressure. Using the known geometry of the orifice plate and know density of the air, Reynold's Number was iteratively solved. The solved Reynold's Number was then used to calculate the velocity of the cooling air. Finally, the mass flow rate of the cooling air was calculated using density, area of orifice plate, and velocity. The mass flow rate will be used to perform conjugate heater transfer analysis to calculate the near-surface coupon temperature at the cooling channel.

Data_Reduction_Program_V2

```
%% Changing Variables
data.P_10psi.Temp.FlowTemp = 293.15;    %ambient air flow temp - K%
data.P_10psi.Reynolds.Guess = 100000;
Patm = 101325;    %atmopheric pressure - Pa%
k = 1.4;
desiredPrecision = 0.0000001;

Misc.dataPath = [cd, '\\'];
Misc Filename_10psi = ['40psi.tdms'];

RawData.P_10psi = TDMS_getStruct([Misc.dataPath Misc.Filename_10psi]);

%% Organize Data
data.P_10psi.Pressure.Downstream(:,1) =
RawData.P_10psi.Untitled.Static_Pressure_Before_Orifice.data(1,:);    %V%
data.P_10psi.Pressure.Diff(:,1) =
RawData.P_10psi.Untitled.Differential_Pressure_Transducer.data(1,:);    %V%
data.P_10psi.MassFlow.MFM(:,1) =
RawData.P_10psi.Untitled.Mass_Flow_Meter.data(1,:);    %V%
data.P_10psi.Time(:,1) =
0:(1/100):(length(data.P_10psi.Pressure.Downstream)/100);    %V%

%% Convert Voltages to Pressures
data.P_10psi.Pressure.Downstream(:,1) =
20.085*data.P_10psi.Pressure.Downstream(:,1)-0.2431;    %psi%
data.P_10psi.Pressure.Diff(:,1) = 10*data.P_10psi.Pressure.Diff(:,1)-0.5;
%psi%
data.P_10psi.Pressure.Upstream(:,1) = data.P_10psi.Pressure.Downstream(:,1) +
data.P_10psi.Pressure.Diff(:,1);    %psi%

%% Convert to Pa
data.P_10psi.Pressure.Downstream(:,1) =
6894.76*data.P_10psi.Pressure.Downstream(:,1);    %Pa%
data.P_10psi.Pressure.Diff(:,1) = 6894.76*data.P_10psi.Pressure.Diff(:,1);
%Pa%
data.P_10psi.Pressure.Upstream(:,1) =
6894.76*data.P_10psi.Pressure.Upstream(:,1);    %Pa%

%% Geometry of Orifice Plate
dOrificeplate = 0.2795*0.0254; %opening of the hole in orifice plate - m%
DIncomingPipe = 0.43*0.0254; %I.D. of pipe - m%
```

```

Beta = dOrificeplate/DIncomingPipe; %dimensionless diameter ratio%
Aorificeopening = (pi*(dOrificeplate)^2)/4; %area of orifice opening - m^2%

%% Density
Rbar = 8314.4; %Universal Gas Constant - J/kmol*K&
MWAir = 28.97; %kg/kmol%
R = Rbar/MWAir; %J/(kg*K)
data.P_10psi.Density(:,1) =
(data.P_10psi.Pressure.Upstream(:,1)+Patm)./(R*data.P_10psi.Temp.FlowTemp);
%kg/m^3%

%% Expansibility Factor
epsilon(:,1) = 1 - ((0.374+0.405*(Beta^4)+0.193*(Beta^8))*(1-
(data.P_10psi.Pressure.Downstream(:,1)./data.P_10psi.Pressure.Upstream(:,1)).
^(1/k)));

escape = 0;
while escape ==0;

%% Discharge Coefficient
A = (19000*Beta/data.P_10psi.Reynolds.Guess)^0.8; %Constant in Equation
L_1 = 0; %Constant with value 0 for Corner Tapped Orifice Plates
L_2 = 0; %Constant with value 0 for Corner Tapped Orifice Plates
M_2 = 2*L_2/(1-Beta); %Constant used in Formula

%Reader-Harris/Gallagher equation for discharge coefficient
dischargeCoefficient = 0.5961+(0.0261*(Beta^2))-(0.216*(Beta^8))...
+0.000521*((10^6)*Beta/data.P_10psi.Reynolds.Guess)^0.7)...

+((0.0188+0.0063*A)*(Beta^3.5)*((10^6)/data.P_10psi.Reynolds.Guess)^0.3))...
+(0.043+0.080*exp(-10*L_1)-0.123*exp(-7*L_1))*(1-0.11*A)*((Beta^4)/(1-
Beta^4))...
-0.031*(M_2-0.8*M_2^1.1)*Beta^1.3...
+0.011*(0.75-Beta)*(2.8-((DIncomingPipe)/0.0254));

%% Mass Flowrate of Orifice Meter
for i =1:length(data.P_10psi.Pressure.Diff)
    data.P_10psi.MassFlow.Orifice(i,1) = (dischargeCoefficient/sqrt((1-
(Beta^4))))*epsilon(i,1)...

*Aorificeopening*sqrt(2*data.P_10psi.Density(i,1)*data.P_10psi.Pressure.Diff(
i,1)); %kg/s%
end

%% Velocity from Orifice Meter Mass Flow
data.P_10psi.Velo(:,1) =
data.P_10psi.MassFlow.Orifice(:,1)./(data.P_10psi.Density(i,1)*Aorificeopenin
g); %m/s%

%% Viscosity
b = 1.458*10^(-6); % (kg/(m*s*K^(.5)))%
s = 110.4; %K%
data.P_10psi.Visc =
(b*data.P_10psi.Temp.FlowTemp^(3/2))./(data.P_10psi.Temp.FlowTemp+s);

```

```

%% Reynolds Number from Orifice
data.P_10psi.Reynolds.Actual =
data.P_10psi.Density.*data.P_10psi.Velo.*dOrificeplate/data.P_10psi.Visc;

%% Reynolds Number Iteration
data.P_10psi.Reynolds.Diff = abs(data.P_10psi.Reynolds.Guess-
mean(data.P_10psi.Reynolds.Actual));
if data.P_10psi.Reynolds.Diff >=0
    data.P_10psi.Reynolds.Guess = data.P_10psi.Reynolds.Guess -
0.5*(10.^floor(log10(data.P_10psi.Reynolds.Diff)));
else
    data.P_10psi.Reynolds.Guess = data.P_10psi.Reynolds.Guess +
0.5*(10.^floor(log10(data.P_10psi.Reynolds.Diff)));
end
disp(['Reynolds Diff: ' num2str(mean(data.P_10psi.Reynolds.Diff))])

if abs(data.P_10psi.Reynolds.Diff) < desiredPrecision
    data.P_10psi.Reynolds.Final = data.P_10psi.Reynolds.Guess;
    escape = 1;
end
end

%% Average VFRs and Voltages
avgMFR = mean(data.P_10psi.MassFlow.Orifice(500:end)); %average volumetric
flow rate from inline air heater - m^3/s%
avgDen = mean(data.P_10psi.Density(500:end)); %average density - kg/m^3%
avgVolt = mean(data.P_10psi.MassFlow.MFM(500:end)); %average voltage
reading from inline air heater - V%

```

Appendix C: LabVIEW

The Virginia Tech Aerothermal Rig used a National Instruments DAQ system and LabVIEW to control the test rig during testing. The fuel system, sand injector system, exhaust quenching, and thermocouples were monitored during testing along with the bulk flow velocity. Data from various instrumentation and controls were recorded during testing in National Instruments Test Data Management System formatting (TDMS). Using the *TDMS_readTDMSFile* code, TDMS files were converted to MATLAB files. Finally, the *Injection_Temps_V3_Cool* code was used to select desired measurements, such as temperature measurements during steady-state sand injection period.

TDMS_readTDMSFile

```
function [finalOutput,metaStruct] = TDMS_readTDMSFile(tdmsFileName,varargin)
%TDMS_readTDMSFile  Reads TDMS file and does minimal processing to obtain
output
%
%   [finalOutput,metaStruct] = TDMS_readTDMSFile(tdmsFileName)
%
%   [...] = TDMS_readTDMSFile(tdmsFileName,'Property1',PropertyValue1,...)
%   allows for specification of additional properties.
%
%   [...] = TDMS_readTDMSFile(tdmsIndexFileName,...)  Allows you to pass
%   in the tdms_index file for debugging
%
%   This is the main file for reading TDMS files.  It reads the file and
%   does minimal processing on the output.
%
%   For wrappers of this function (RECOMMENDED):
%   See Also:
%       TDMS_getStruct
%       TDMS_dataToGroupChanStruct_v1,
%       TDMS_dataToGroupChanStruct_v2,
%       TDMS_dataToGroupChanStruct_v3,
%       TDMS_dataToGroupChanStruct_v4
%       TDMS_readChannelOrGroup
%
%   RETRIEVING PARTIAL DATA
%   =====
%   This code has the ability to retrieve a subset of the data from the
%   tdms file.  For documentation on this see: TDMS_retrievingSubsets
%
%   OUTPUTS:
%   NOTE: Wrappers exist to change this to a preferred format.  See above.
%   =====
%   finalOutput : (struct)
%   -----
%       .rootIndex      - index of the root
%       .groupIndices   - (numeric array) indices of all group objects
%       .chanIndices    - (cell array of numeric arrays)
%                       ex. {[1 2]   [3 4 5]   [6 7 8]}
%                       Each index in the cell array corresponds to the
%                       same index in groupNames and groupIndices
%                       At that index is an array of indices for the
%                       channel objects that belong to that group
```

```

%      .chanNames      - (cell array of cell array of strings)
%                        ex. {{ '1' '2' } { '3' '4' '5' }}
%                        similar setup to chanIndices
%      .groupNames     - (cell array of strings) names of each group object
%
%      For the following properties, the indices referred to above ,
%      groupIndices and chanIndices, index into these arrays:
%      .data            - (cell array, # elements = # objects)
%      .propNames       - (cell array of cell arrays)
%      .propValues      - (cell arrays of cell arrays)
%      .dataType        - (num. array) Labview dataType enumeration
%      .dataTypeName    - (cell array of strings)
%      .objectPathsOrig - (cell array of strings) This is thrown in for
%                        reference and is the full name of the object as
%                        tracked in the TDMS file
%      .numberDataPointsRaw - The # of data points for each object that
%                        are available in the TDMS file. This is not
%                        filtered, thus it may not match the # of
%                        data points returned in .data
%
% metaStruct : (struct)
% -----
%      This output is essentially a dumping ground for a lot of the
%      temporary variables in the code and may change between versions.
%      .version        - indicates which version of the code was used
%                        to create this structure
%      .fileName       - relative name (no path) of the tdms file on which
%                        this structure is based
%      .numberDataPoints - # of data points available for each channel
%      .chanNames      - channel name for each object, empty for channels &
%                        root
%      .groupNames     - group name for each object
%      OTHER VARIABLES IN metaStruct MAY CHANGE ...
%
%      OPTIONAL PARAMETERS: pass in as property/value pairs, case insensitive
%      =====
%      UTC_DIFF        : (default -5) Conversion of UTC Timestamp to local
%                        time, if desired this can be set to 0 and no
%                        conversion will occur
%
%                        Eastern Time: -5, Central Time: -6
%
%      USE_INDEX       : (default true) If true, reads the tdms_index file
%                        if it is available. This may offer some speedup in
%                        reading the file.
%
%      MAX_NUM_OBJECTS : (default 100) This is currently used in preallocation
%                        of the # of objects. On overflow the same # is used
%                        to grow by, i.e. on object 101, grow to 200
%
%      MAX_NUM_PROPS   = (default 20), used for initializing property cell
%                        arrays for each object
%
%      N_SEGS_GUESS    = (default 25000), estimated # of segments for
%                        preallocation purposes
%

```

```
% N_SEGS_INC      = (default 25000), how much to expand upon segment
%                  overflow, i.e. if more than N_SEGS_GUESS segments
%
% DATE_STR_FORMAT = (default 'dd-mmm-yyyy HH:MM:SS:FFF'), how to process
%                  the timestamp properties, timestamp arrays (i.e.
%                  data) are left in the same format as Matlab's now
%                  command, i.e. a numeric value that you can call the
%                  function datestr() on to return a value
%
% INIT_CHUNK_SIZE = (default 1000), the expected # of chunks of data,
%                  this probably shouldn't be changed ...
%
% Additional properties are defined in TDMS_retrievingSubsets
```

```
%FUNCTIONS CALLED IN THIS FILE:
```

```
%=====
```

```
%      TDMS_handleGetDataOption
%      TDMS_preprocessFile
%      TDMS_getGroupChanNames
%      TDMS_processLeadIn
%      TDMS_readFileHelper_v2
%      TDMS_readFileHelper_v1
```

```
if nargin == 0
    error('Input to %s requires a filename',mfilename)
end
```

```
if ~exist(tdmsFileName,'file')
    error('The file specified for tdms reading doesn''t exist, FILENAME:
%s',tdmsFileName)
end
```

```
%Added to allow for tdms_index reading
[~,~,fileExt] = fileparts(tdmsFileName);
```

```
%DON'T CHANGE ME
```

```
%=====
```

```
temp = [who; {'temp'}];
STRING_ENCODING = 'UTF-8';
SECONDS_IN_DAY = 86400; %60s * 60 min * 24 hours
CONV_FACTOR = 695422; %datenum('01-Jan-1904')
ROOT_PATH = '/';
ROOT_GROUP_NAME = '';
TDMS_INDEX_EXT = '.tdms_index';
MACHINE_FORMAT = 'ieee-le'; %NOTE: Eventually this could be passed into
%fread for support of different endianness
CURRENT_VERSION = 2.5;
constantParams = setdiff(who,temp); %NOTE: Below I place these into the
%constants variable structure but I don't allow assignment from inputs
```

```
%PROPERTIES THAT MIGHT NEED TO BE CHANGED
```

```

%=====
temp = [who; {'temp'}];
%The following get passed down into TDMS_preprocessFile
UTC_DIFF      = -5;    %#ok<*NASGU> %This will report times in Eastern
Standard Time
USE_INDEX      = true; %Parse meta data from index if present
MAX_NUM_OBJECTS = 100; %Best guess as to max # of objects ever encountered
MAX_NUM_PROPS  = 20;   %" " properties " "
N_SEGS_GUESS   = 25000;%same, but for segments
N_SEGS_INC     = 25000;%if off, how large to grow estimate by when resizing
DATE_STR_FORMAT = 'dd-mmm-yyyy HH:MM:SS:FFF'; %default conversion of property
value

                %NOTE: data values are not converted, but run datestr()
                %on them if you wish to see their value as a string
INIT_CHUNK_SIZE = 1000; %a chunk is a subset of a segment, the # of chunks
                        %varies on an object by object basis, only applies
                        %to objects with raw data

DEBUG          = false; %Internal use

%NOTE: INDEX_DEBUG indicates that we'll only attempt to read the index
%file, no raw data will be read
if strcmp(fileExt, '.tdms_index')
    INDEX_DEBUG      = true;
else
    INDEX_DEBUG      = false;
end

OBJECTS_GET      = struct([]);
OBJECTS_IGNORE   = struct([]);
SUBSET_GET       = [];
GET_INDICES      = []; %Needs fields 'group' 'channel' 'indices'
SUBSET_IS_LENGTH = true;
GET_DATA_OPTION  = 'getAll';
META_STRUCT      = []; %Can be used to reduce processing time
                  %This is an output from this file
defaultOPTS     = setdiff(who,temp); %Anything in defaultOPTS can be
overwritten
%below if the name matches a property name from the input

%Assignment of default values, as well as paramsStruct population
%-----
paramsStruct = struct;
if nargin > 1
    defNames = varargin(1:2:end);
else
    defNames = {};
end

for iDefault = 1:length(defaultOPTS)
    curVariable = defaultOPTS{iDefault};
    I = find(strcmpi(curVariable,defNames),1);
    if ~isempty(I)
        eval([curVariable '= varargin{2*I};'])
    end
    paramsStruct.(curVariable) = eval(curVariable);
end

```

```

end

for iConst = 1:length(constantParams)
    curVariable = constantParams{iConst};
    paramsStruct.(curVariable) = eval(curVariable);
end
%paramsStruct now contains all constants, as well as their values

%Data option checking
%-----
TDMS_handleGetDataOption('check',paramsStruct)

%File Opening & meta data processing
%-----
if ~INDEX_DEBUG
    fid = fopen(tdmsFileName,'r',MACHINE_FORMAT,STRING_ENCODING);
else
    fid = []; %Don't open the .tdms file, .tdms_index only
end

metaStruct = TDMS_preprocessFile(fid,tdmsFileName,paramsStruct);
metaStruct = TDMS_getGroupChanNames(metaStruct); %Processing of channel &
group names
optionStruct = TDMS_handleGetDataOption('getArray',paramsStruct,metaStruct);
%Option handling

%Property handling
%-----
rawDataInfo = metaStruct.rawDataInfo;
numObjects = length(rawDataInfo);
propNames = cell(1,numObjects);
propValues = cell(1,numObjects);
for iObject = 1:numObjects
    propNames{iObject} = rawDataInfo(iObject).propNames;
    propValues{iObject} = rawDataInfo(iObject).propValues;
end

%Getting the data
%-----
if strcmpi(GET_DATA_OPTION,'getNone') || INDEX_DEBUG
    data = cell(1,length(metaStruct.rawDataInfo));
    if ~INDEX_DEBUG
        fclose(fid);
    end
elseif optionStruct.useSubset
    data = TDMS_readFileHelper_v2(fid,optionStruct,metaStruct,paramsStruct);
else
    data = TDMS_readFileHelper_v1(fid,optionStruct,metaStruct,paramsStruct);
end

%INITIALIZATION OF GENERIC OUTPUT
%=====
%use groupInfo = TDMSp_getGroupInfo(groupNames,chanNames,isChan) instead

```

```

[uGroups,~,Igroup] = unique(metaStruct.groupNames);
%NOTE: Igroup tells us which of the unique group names each index belongs to

rootIndex = find(cellfun(@(x)
strcmp(x,ROOT_PATH),metaStruct.objectNameList));

groupIndices      = zeros(1,length(uGroups)-1);
chanIndices       = cell(1,length(groupIndices));
groupNamesOutput  = cell(1,length(groupIndices));
chanNamesOutput   = cell(1,length(groupIndices));

curGroupCount = 0;
for iGroup = 1:length(uGroups)
    if ~strcmp(uGroups(iGroup),ROOT_GROUP_NAME)
        curGroupCount = curGroupCount + 1;

        %Find all those with matching group name
        inGroup = find(Igroup == iGroup);

        %Parse out the actual group object
        isGroupObject = ~metaStruct.isChan(inGroup);
        I_groupObject = inGroup(isGroupObject);
        groupIndices(curGroupCount) = I_groupObject;
        groupNamesOutput(curGroupCount) = uGroups(iGroup);

        %Parse out the channels for that group
        inGroup(isGroupObject) = [];
        chanIndices{curGroupCount} = inGroup;
        chanNamesOutput{curGroupCount} = metaStruct.chanNames(inGroup);
    end
end

finalOutput = struct(...
    'rootIndex',rootIndex,...
    'groupIndices',groupIndices,...
    'groupNames',{groupNamesOutput},...
    'chanIndices',{chanIndices},...
    'chanNames',{chanNamesOutput},...
    'data',{data},...
    'propNames',{propNames},...
    'propValues',{propValues},...
    'objectPathsOrig',{metaStruct.objectNameList},...
    'numberDataPointsRaw',metaStruct.numberDataPoints,...
    'dataType',[rawDataInfo.dataType],...

    'dataTypeName',{arrayfun(@TDMS_getDataTypeName,[rawDataInfo.dataType],'Unifor
mOutput',false)});
end

```

Injection_Temps_V3_Cool

```

%% Load data
[FileName, PathName, ~] = uigetfile('*.mat');

```

```

Tmp = load([PathName FileName]); % Temporary variable

%Downsizing Coolant Flowmeter data by a factor of 200
CoolantFlowmeter2 =
downsample(Tmp.my_tdms_struct.Untitled.CoolantFlowmeter.data,200);
Tmp.my_tdms_struct.Untitled.CoolantFlowmeter2.data = CoolantFlowmeter2;

%Downsizing Coolant Pressure Transducer data by a factor of 200
CoolantPressure2 =
downsample(Tmp.my_tdms_struct.Untitled.CoolantPressure.data,200);
Tmp.my_tdms_struct.Untitled.CoolantPressure2.data = CoolantPressure2;

RawData = Tmp.my_tdms_struct.Untitled; % shrink structure

clear Tmp FilterIndex

%% Pick Temperatures
FieldNames = fieldnames(RawData);

% Select wanted variables
[t, ~] = listdlg('PromptString', 'Select Time Stamp Variable:', ...
    'SelectionMode', 'multiple', ...
    'ListString', FieldNames);

% Select wanted variables
[s, ~] = listdlg('PromptString', 'Select Variables:', ...
    'SelectionMode', 'multiple', ...
    'ListString', FieldNames);

% Reformat each variable into a table
% Time stamp table
name = FieldNames(t(1));
R = array2table(RawData.(name{1}).data, 'VariableNames', name);

% setup new table
Out = table;
Out = [Out,R];
% Remaining variables
for i = 1:size(s,2)
    name = FieldNames(s(i));
    R = array2table(RawData.(name{1}).data, 'VariableNames', name);

    % Horizontally concatenate
    Out = [Out, R];

end
clear i name R

TempHr = datestr(Out.Time, 'HH');
TempMin = datestr(Out.Time, 'MM');
TempSec = datestr(Out.Time, 'SS.FFF');

for i = 1:size(Out,1)
    Out.Hr(i) = str2double(TempHr(i,:));

```

```

        Out.Min(i) = str2double(TempMin(i,:));
        Out.Sec(i) = str2double(TempSec(i,:));

end
clear i TempHr TempMin TempSec

Out.TotSec = 3600.0*(Out.Hr) + 60.0*(Out.Min) + Out.Sec;
Start = Out.TotSec(1);
Out.Hr = []; Out.Min = []; Out.Sec = []; % clear variables

Out.Time1 = Out.TotSec - Start; % new time stamp

% clear variables
Out.TotSec = []; Out.Time = [];
clear start

% reorganize variables for plotting
X = Out.Time1;
Out.Time1 = [];
Y = [Out];

%% Plot and select data

xlimits = 'No';
while strcmp(xlimits, 'No')

    % Plot coupon temperatures
    %f = figure;
    plot(X, Y.Variables)
    xlabel('Time (s)')
    ylabel('Temperature (°C)');
    ylim([400 1150])
    xlim([1725 2025])
    hold on;
    % Select the estimate injection start time
    uiwait(msgbox(...
        'Select the estimate injection start time'));

    [Time_Inj(1), ignore] = ginput(1); % mouse click to estimate the min time
    Time_Inj(1) = round(Time_Inj(1),1); % find the injection time

    % find the temperatures during the injection period
    input = inputdlg('Injection duration (sec):');
    Time_Inj(2) = str2double(input{1})+Time_Inj(1);

    % Plot lines from inputs that highlights the injection period
    X2 = [Time_Inj(1), Time_Inj(1)];
    Y2 = [0, 1150];
    X3 = [Time_Inj(2), Time_Inj(2)];
    Y3 = Y2;
    plot(X2,Y2,X3,Y3)
    hold on;

    % reset x-limits to correlate to around the injection time period

```

```

xlim([Time_Inj(1)-100 Time_Inj(2)+100])
grid on;

xlimits = questdlg('Are you happy with the limits?','','...
    'Yes','No','No');
%close(f);
end

% set range of time for injection
Range = logical((X <= Time_Inj(2)) .* (X >= Time_Inj(1)));
% Calculate average value during injection
name = Y.Properties.VariableNames;
for i = 1:size(Y,2)
    Avg.(name{i}) = mean(Y.(name{i})(Range,:));
end

```