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I, Paul P. Aghasi, hereby submit this original work as part of the requirements for the degree of Master of Science in Aerospace Engineering.

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Dependence of Film Cooling Effectiveness on 3D Printed Cooling Holes

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ABSTRACT

To investigate the viability of using additive manufacturing technology for flat plate film cooling experiments a new experiential facility was constructed using gas analysis and oxygen sensitive paint as a method of measuring and characterizing film cooling effectiveness for various additive manufacturing technologies as well as aluminum. The ultimate objective of this work is to assess whether these technologies can be a replacement for traditional aluminum CNC machining.

Film Cooling Effectiveness is closely dependent on the geometry of the hole emitting the cooling film. These holes are sometimes quite expensive to machine by traditional methods so 3D printed test pieces have the potential to greatly reduce the cost of film cooling tests. What is unknown is the degree to which parameters like layer resolution and the choice of 3D printing technologies influence the results of a film cooling test. A new flat-plate film cooling facility employing the mass transfer analogy (introduction of foreign gas as coolant, not to be confused with the sublimation method) and measurements both by gas sample analysis and oxygen-sensitive paint is first validated using gas analysis and oxygen sensitive paint cross correlation. The same facility is then used to characterize the film cooling effectiveness of a diffuser shaped film cooling hole geometry. These diffuser holes (film hole diameter, D of 0.1 inches) are then produced by a variety of different manufacturing technologies, including traditional machined aluminum, Fused Deposition Modeling (FDM), Stereo Lithography Apparatus (SLA) and PolyJet with layer thicknesses from $0.001D$ ($25\text{ }\mu\text{m}$) to $0.12D$ ($300\text{ }\mu\text{m}$). Tests are carried out at mainstream flow Mach number of 0.30 and blowing ratios from 1.0 to 3.5. The coolant gas used is CO_2 yielding a density ratio of 1.5. Surface quality is characterized by an Optical Microscope

that calculates surface roughness. Test coupons with rougher surface topology generally showed delayed film hole blow off and higher film cooling effectiveness at increased blowing ratios compared to the geometries with lower measured surface roughness.

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NOMENCLATURE

$\frac{I_{ref}}{I}$	Image intensity ratio
N''	Molar flux
q''	Heat flux
A	Inlet flow area
Al	Aluminum
AM	Additive Manufacturing
BR	Blowing Ratio
CCD	Charge coupled device
C_D	Discharge coefficient
CNC	Computer Numerical Control
C_p	Constant pressure specific heat capacity
C_x	Mass concentration of substance x
D	Diameter of film cooling hole
D_{AB}	Binary diffusion coefficient
DR	Density Ratio
FDM	Fused Deposition Modeling
g	Acceleration due to gravity
h	Enthalpy
h	Heat transfer coefficient
h_m	Convective mass diffusivity
I	Momentum flux ratio
k	Conductivity
L	Hole length
Le	Lewis number
M	Mach number
$\dot{m}$	Mass flow
mil	1/1000 th of an inch
Nu	Nusselt number
OSP	Oxygen Sensitive Paint
P	lateral distance between holes, pitch
P	Pressure
Pr	Prandtl number
psig	Pounds per square inch gauge
PSP	Pressure Sensitive Paint
R	Universal gas constant

Ra	Surface roughness in mils
s	Entropy
Sc	Schmidt number
Sh	Sherwood number
SLA	Stereo Lithography Apparatus
St	Stanton number
T	Temperature
t	Film cooling hole coverage width
Tu	Mainstream turbulence intensity
U	Velocity magnitude
UV	Ultraviolet
V	Velocity
W	Molecular weight
X	Pitchwise distance measured from center hole
X	Molar fraction
Y	Downstream distance measured from pierce point of hole metering axis

GREEK

β	Expansion angle for diffused outlet
γ	Ratio of specific heat constants
δ	99% boundary layer thickness
Δ	Difference
η	Local adiabatic film effectiveness
μ	Micro meters
ρ	Fluid density

SUBSCRIPTS

0	Total (pressure / temperature / density)
∞	mainstream
aw	Adiabatic wall
c	Coolant
c	Concentration
e	Effective / ideal
f	Local flow
FH	Film holes
fwd	forward expansion of shaped hole
g	Gas
lat	lateral expansion of shaped hole (half-angle)

m	metering section
ref	Reference
s	Surface
t	Thermal
w	Wall

SUPERSCRIPTS

—	Laterally Averaged
=	Area averaged
*	Dimensionless
*	Choked

CHAPTER 1: INTRODUCTION

Increasing efficiency of gas turbines by employing higher gas temperatures in combustors and turbines promotes reduction in fuel cost, reduction in carbon emissions and improvement in performance of aircraft, marine vessels, and power plants. The improvement in gas turbine performance can be illustrated by the Brayton cycle h-s diagram.

Figure 1 Brayton cycle h-s diagram illustrating potential performance improvement by increasing turbine inlet temperatures

At process 1, adiabatic compression from ambient pressure takes place where work is done on the fluid to raise its enthalpy by Δh_1 (typically in a gas turbine compressor). Process 2 signifies constant pressure heat addition where the enthalpy of the fluid is raised by Δh_2 (typically in a gas turbine combustor). Then in process 3 work is extracted from the fluid by the value of Δh_3 to sustain process 1 (typically in the turbine component of a gas turbine). The value of Δh_3 is the same as Δh_1 if the mass flow for both processes are kept constant (typically not true due to fuel addition at process 2, however a good assumption for this analogy). At process 4

useful work is extracted from the fluid in various forms e.g. in a nozzle for propulsion or a power turbine to drive a generator or a propeller. There are many ways of improving the output work of a gas turbine system. One is to simply increase the turbine inlet temperature by extending process 2 by an additional Δh_a . In this scenario, since Δh_1 stays the same, Δh_3 is also unaffected. Therefore Δh_4 can be increased to Δh_{4a} . However, there is a limit on how much turbine inlet temperature can be increased to increase output work. This limit is due to the turbine alloy maximum achievable service temperature. Film cooling enables metal parts to operate in gas temperatures that would otherwise be impossible. Film cooling can also be used to improve the part longevity. A 25° K reduction in the turbine blade surface temperature can result in doubling of its life [1]. The motivation behind film cooling research is to improve the capability for coolant flow field prediction and optimization.

Flat plate film cooling experimentation has been a fundamental performance assessment tool of the film hole geometries for many decades. It is of utmost importance to ensure that the results from such experimentation are interpreted correctly. The present work investigates the application of 3D printing techniques as a tool to manufacture film cooling hole geometries for flat plate film cooling experimentation, with varying build layer thicknesses to assess whether these techniques are a reasonable substitute for traditional aluminum CNC machining.

After initial validation using gas analysis and oxygen sensitive paint, the 7-7-7 diffusing hole geometry outlined in [2] was utilized for this investigation.

1.1 FILM COOLING THEORY

The overall goal of turbine film cooling technology is to decrease airfoil temperatures to prolong turbine lifetime or to increase the turbine inlet temperature for the increase in gas turbine

useful work. One way to increase the lifetime of the turbine blade is to reduce the heat transfer rate next to blade surface. This can be achieved by reducing the local fluid temperature close to the airfoil surface. Heat transfer to the turbine blades is typically modeled using a convective heat transfer coefficient:

$$q'' = h(T_{ref} - T_w) \quad \text{Eq. 1.1}$$

Where q'' is the heat flux (heat transfer per unit area), h is the convective heat transfer coefficient, T_w is the wall temperature and T_{ref} is a reference temperature which needs further definition. In the case of film cooling T_{ref} is defined based on two temperatures namely the coolant temperature and the mainstream temperature. In the case of film cooling, T_{ref} in Eq. 1.1 is the gas temperature adjacent to the surface. If the surface is adiabatic, then q'' is zero, and T_{ref} is T_w .

An ideal film cooling arrangement introduces a layer of coolant fluid at a uniform temperature T_c between a wall at T_w and a hot gas at T_∞ . This ideal condition is adversely affected by mixing between the outer flow and the film fluid. In a real system the film temperature T_f matches T_c as it exits a cooling hole and increases as it mixes with the hot outer flow. T_f varies across the surface of the wall and also with height above the wall. $T_f = T_{aw}$ when the wall material is adiabatic. Because the adiabatic wall temperature T_{aw} is the fluid temperature immediately above the surface, it is a good reference temperature for film cooling. Therefore, the heat flux for film cooling can be re-written as:

$$q'' = h_f(T_{aw} - T_w) \quad \text{Eq. 1.2}$$

To predict airfoil temperatures it is important to predict the adiabatic wall temperature which can be regarded as the fluid temperature adjacent to the metal surface. This adiabatic wall

temperature is a very important variable in airfoil surface temperature prediction. It is convenient to non-dimensionalize T_f as film cooling effectiveness η so that it can be related to engine operating temperatures (Figure 2):

$$\eta = \frac{T_{\infty} - T_f}{T_{\infty} - T_c} \quad \text{Eq. 1.3}$$

Figure 2 Thermal profiles of coolant jet, decay of the normalized temperature θ downstream of hole, η is θ at the surface [1].

Figure 3 anatomy of a cooled blade [1]

Figure 3 shows the anatomy of a cooled blade. The compound angle is the angle at which the stream wise orientation of the hole makes with the mainstream flow. T_g is the gas temperature right above the blade wall, T_c is the coolant temperature right before getting injected into the mainstream flow and T_w is the metal temperature right at the wall in contact with the flow.

An η value of 0.30 indicates that the temperature of the gas at that location is 30% between the coolant temperature and the main temperature. Unless otherwise noted, all references to η in this work are to η at the surface. The art of film cooling design is then to

introduce the cooling film in a way that spreads the coolant flow laterally as fully as possible, to minimize the mixing of the cooling film with the outer flow, and to use the minimum amount of coolant flow.

Sometimes structural concerns prohibit the use of cooling slots on turbine blades, so the design challenge is to optimize the design of discrete cooling holes. Figure 4 shows an example of such a device. Discreet film cooling holes can be seen on the leading edge, pressure side and at the tip.

Figure 4 Modern high pressure turbine blade where discreet film cooling holes in the leading edge, pressure side and tip are visible

Although there are many open questions about the formation of a cooling film from discrete holes, a significant published literature has been produced over the last 35 years (for example [1, 3, 4, 5]) in order to isolate the effects of film cooling hole geometry from other considerations such as wall curvature, end-wall effects and rotating-reference-frame effects and to achieve this, it is common to test hole geometries on flat plates. Known factors affecting film cooling performance are listed in Table 1. Factors with a large effect on film cooling performance predictability are included in bold.

**Table 1 factors affecting film cooling performance [1],
significant factors are presented in bold**

Coolant/mainstream conditions	Hole geometry and configuration	Airfoil geometry
Blowing Ratio or Mass flux ratio (BR)	Shape of the hole	Hole location:
Momentum flux ratio (I)	Injection angle and compound angle of the coolant hole	Leading edge
Mainstream turbulence	Spacing between holes	Pressure side
Coolant density ratio	Length of the hole	Suction side
Approach boundary layer	Spacing between rows of holes and number of rows	Blade tip
Mainstream Mach number		Endwall
Unsteady mainstream flow		Surface curvature
Rotation		Surface roughness

The parameters that are relevant to the current work will be discussed in the following paragraphs. The present work has uncovered that another parameter, not known previously, could be at play and that is the film cooling hole interior roughness. It is not known however how significant this parameter is.

Blowing Ratio (BR) is defined as the ratio of coolant mass flux (mass flow per unit area) to that of the mainstream. It is typically expressed as:

$$BR = \frac{\frac{\dot{m}_c}{A_c}}{\frac{\dot{m}_\infty}{A_\infty}} = \frac{(\rho_c U_c)}{(\rho_\infty U_\infty)} \quad \text{Eq. 1.4}$$

Where $\dot{m}_c$ is coolant mass flow rate, A_c is coolant injection area, ρ_c is coolant density, U_c is coolant velocity magnitude, $\dot{m}_\infty$ is mainstream mass flow rate, A_∞ is mainstream flow area, ρ_∞ is mainstream density and U_∞ is mainstream velocity magnitude.

Momentum flux ratio (I) is defined as the fluid momentum ratio per unit area. Its mathematical expression is essentially BR multiplied by coolant to mainstream velocity ratio:

$$I = \frac{\rho_c U_c}{\rho_\infty U_\infty} \times \frac{U_c}{U_\infty} = \frac{\rho_c U_c^2}{\rho_\infty U_\infty^2} \quad \text{Eq. 1.5}$$

BR and I can be used to match film cooling performance to engine conditions especially when laboratory tests use lower coolant to mainstream Density Ratio (DR) than engine operating conditions. Since the convective heat transfer coefficient can be written as $C_p \rho U_c$ [1], BR is used to scale the measure of the coolant thermal transport. Momentum flux ratio (I) is used to scale the coolant and mainstream inertial interaction [1]. This is of importance because typically in film cooling flow the mainstream flow turns the coolant jet towards the metal wall by this inertial interaction, and it has a significant effect on cooling performance. Should the mainstream flow not have enough momentum to turn the coolant jet sufficiently, the majority of the coolant jet steam tube will be separated and mixed with the mainstream flow instead of staying attached to the metal surface to provide cooling. The shear layer between the coolant jet and the mainstream can be scaled with the velocity ratio and can be used to estimate turbulence production. Only one of the mentioned scaling parameters can be matched to engine conditions if DR does not match engine operating conditions [1].

Coolant density ratio increase can boost film cooling performance. For the round holes the higher improvement has been reported at higher mainstream turbulence intensities [6].

The approach boundary layer plays a role in film cooling performance. The thin approach boundary layer causes the coolant jet to encounter a greater “force” upon injection into the mainstream than in a thicker approach boundary layer. This makes the coolant jet turn faster which is then remained closer to the wall that results in higher film effectiveness. This effect is most influential at BR of close to 0.5 for round holes [7].

There are three distinct flow regimes associated with film cooling. These are illustrated in Figure 5 with data provided by Thole et al. [8]. In Figure 5(a) coolant jets are fully attached, in (b) they are detached then reattached and in (c) they are fully detached or commonly referred to as blown-off or film lifted off.

Figure 5 Thermal field profiles along centerline of coolant jets; from top to bottom: fully attached coolant, detached then reattached coolant and completely detached coolant [8]

Film cooling hole geometries consist of two types: round holes and shaped holes. oftentimes, velocity reduction of the coolant flow is beneficial to the film cooling mechanism because the slowed down coolant flow can now change its direction more easily to align itself with the mainstream flow and keep itself attached to the injection wall.

To demonstrate this, it is beneficial to observe the typical behavior of a round hole with 30° injection angle is plotted in Figure 6. For the case of the round hole, the separation of the coolant flow due to blowing ratio increase starts to appear at blowing ratio of 0.85.

Figure 6 Separation of the coolant flow due to high blowing ratio (M) and momentum flux ratio (I) from [9], DR = 1.8 with 30° injection angle

In contrast, as presented in Figure 7, a shaped hole performs in a different way. In this case, the coolant flow separation is delayed to BR of 2.0 which is a significant improvement.

Figure 7 Shaped film cooling hole η contours for DR of 1.2, (a) BR = 0.51, (b) BR = 1, (c) BR = 2 and (d) BR = 3 from [2]

Shaped holes feature a shaped passage of coolant air near the metal surface. They typically diffuse the coolant so that it gains better coverage, is more resistant to separation at higher blowing ratios and experiences higher effectiveness values compared to round holes. This is achieved by reducing the coolant jet velocity when it passes through the diffusing passage of the hole [3]. The shaped film cooling hole starts off with a round section which acts as a metering section or commonly referred to as the throat that expands into a diffuser-like outlet which is designed to spread the coolant span wise (laterally) and/or onto the surface. The shape is typically bound to the outer 20-50% [3] of the turbine wall thickness. The objective of the shaped film cooling holes is to diffuse and expand the injection plane (film hole outlet) of the round hole by a factor of 2-3 without experiencing flow separation in the diffuser section. A partial catalogue of shaped film cooling holes is provided in Table 2, the film hole type column refers to hole types specified in Figure 8.

Table 2 Partial catalogue of shaped film cooling hole literature including current study [3]

Source	Type	L/D	LT / D	α	β	δ	compound angle	hole spacing P/D	BR	Data Type
Present Study	A	6	2.5	30	7	7	0	6	1.0 - 3.5	local and span averaged film effectiveness, discharge coefficients
Goldstein et al. [10]	B	5.2	1.7	35	10	0	0	3, 6	0.5 - 2.2	Discrete Centerline and lateral effectiveness
Makki et al. [11]	A	~6	~3	35	~10	~10	0	3	0.5 - 4	Span Averaged ratio of HTC with and without film cooling
Sen et al. [12]	C	4	2.1	35	0	15	60	3, 6	0.4 - 2.0	HTC enhancements
Schmidt et al. [13]	C	4	2.1	35	0	15	60	3, 6	0.4 - 2.0	Discrete centerline, lateral and Span Averaged effectiveness
Thole et al. [14]	A, B	6	2	30	14	15, 0	0	infinite	1.0	exit flow field
Kohli et al. [15]	A	4	2	35	15	15	0	infinite	1, 2	CFD effectiveness
Gritsch et al. [16] Gritsch et al. [17]	A, B	6	2	30	14	15, 0	0	infinite	0.5 - 2.0	local and span averaged effectiveness, HTC's
Haven et al. [18]	A, B, D	~6	~2.5, 2.5, 0	35	15	15, 0, 10	0	Unknown	1.0	Flow visualization
Yu et al. [19]	A, C	10	8.4	30	10, 0	10	0	3	0.5, 1.0	local and span averaged effectiveness, HTC's
Kohli et al. [20]	A	2.8	0.9	55	15	15, 25	0	3	0.4 - 1.0	Centerline and span averaged effectiveness
Jackson et al. [21]	D	2.3	0	35	10	10	0	4	0 - 0.65	simulated airfoil aero loss
Reiss et al. [22]	B, C	3.7	1.7	45	15, 0	0, 15	30	3.7	0.6 - 1.5	Multi-row showerhead film effectiveness and HTC
Ganzert et al. [23] Hilderbrandt et al. [24]	A, B	5	1.9	30	10	10, 0	0	5	0.5 - 2.0	airfoil cascade flow field and HTC's, CFD
Bunker [25]	A	5.7	3.2	30	10	10	0	3.6	0.9 - 1.3	centerline effectiveness with and without blockage
Saumweber et al. [26]	B	6	2	30	14	0	0	4	0.5 - 2.5	local and span averaged effectiveness with entrance effects
Takeishi et al. [27]	A	~5	~2	30, 35	9, 12	12, 20, 24	0	2.5, 3	0.8	vane and blade cascade pressure and suction side effectiveness
Barthel et al. [28]	C	~5	~2	50	0	~25	0	6	1.0	airfoil cascade flow field
Chen et al. [29]	C	3.5	~1	35	0	~15	0, 45	3	0.5 - 2.0	concave and convex wall effectiveness
Sargison et al. [30]	B	6	2	35	25	0	0	3.5	0.5 - 1.0	span Averaged effectiveness and HTC
Yuen et al. [31]	B	6	2	30	14	0	0	3	0 - 1.7	local and span averaged effectiveness
Dittmar et al. [32]	B	6	2	45	14	0	0, 35	4	0 - 3	local and span averaged effectiveness, HTC's
Ferguson et al. [33] McGrath et al. [34]	A	5.2	~3.5	~50	~15	~15	0, ~45	5	1.5, 3, 4.5	CFD for airfoil cascade pressure side, span averaged data
Ferguson et al. [33] McGrath et al. [34]	A	10	~5	~30	~15	~15	0, ~45	4.4	1, 1.5, 2	CFD for airfoil cascade suction side, span averaged data
Saumweber et al. [35]	B	6	2	30	14	0	0	4	0.5 - 2.5	local and span averaged effectiveness with varied freestream Tu

Table 2 Continued

Saumweber et al. [36]	B	6	2	30	14	0	0	4	0.5 - 2.5	local and span averaged effectiveness for double row of holes
Bohn et al. [37]	B, C	5	2, 4	30	14, 0	0, 10	0	3	2.0	conjugate analysis

Figure 8 Defined geometries for four types of shaped film holes [25]

1.2 FILM COOLING IN A TYPICAL GAS TURBINE SYSTEM

Film cooling technology is typically applied to the first and second stages of the high pressure turbine. Bleed air is routed from the high pressure compressor to feed the internal and external cooling systems. The internal cooling system is commonly referred to as the impingement cooling system and it mainly cools the turbine blade internally. This uses internal passages that maximize convection heat transfer. The internal coolant flow is then ejected

through the film cooling holes for external cooling where it has to minimize the heat transfer to the blade surface. External temperatures can vary between 1400° C to 1600° C depending on the gas turbine system [1]. This will typically use 20-30% of the engine core flow rate to provide cooling [1]. The following section discusses typical high pressure turbine operating conditions taken from [38].

Table 3 Aero-thermodynamic parameters of a typical gas turbine system from [38].

Parameter	Units	Max climb condition
Inlet temperature (T)	°R	2858
Energy ($\Delta h/T$)	Btu/lbm/°R	0.0844
Speed ($N/\sqrt{T}$)	RPM/ $\sqrt{^\circ R}$	236.2
Corrected flow ($W\sqrt{T}/P$)	lbm $\sqrt{^\circ R}$ /sec.psi	17.65
Thermal efficiency	%	91.9
Pressure ratio		2.25
Vane exit Mach		0.89
Blade exit Mach		0.84

Figure 9 Typical coolant flow parameters on a stage 1 turbine from [38].

This first stage vane was designed for the maximum inlet temperature of 1739° C. The total coolant flow required for this design was 6.3% of the core flow [38]. This produced temperature variation outlined in Figure 10. The blade section outlined is located in the mid section.

Figure 10 Stage 1 vane thermal model and detailed temperature distribution at mid section form [38].

The inlet Mach number for each stage at a function of blade height is outlined in Figure 11. Typically the stage 1 Mach number is close to 0.1 and the inlet Mach for succeeding stages hovers around 0.3.

Figure 11 Inlet Mach numbers for each stage as a function of blade height from [38].

Figure 12 Typical turbine airfoil shapes and velocity distributions from [38].

Figure 12 shows the typical Mach number profiles and turbine airfoil shapes. The present study uses a flat plate film cooling facility with mainstream Mach number of 0.3. This is comparable to a suction side vane location. Typically the mainstream flow turbulence intensity is in the order of 25% [1]. Turbulence levels are quantified in terms of velocity fluctuations (rms levels) divided by the magnitude of the mean velocity [1]. The mainstream flow turbulence intensity for the present study at Mach 0.14 was measured to be 0.5%. In Figure 9 the coolant flow has total pressure and temperature of 378.0 psia and 1130° F respectively. The mainstream flow has total pressure and temperature of 366.5 psia and 3163° F respectively. This gives a coolant to mainstream density ratio of 2.3. The present study uses CO₂ as coolant giving coolant

to mainstream density ratio of 1.5. The use of a foreign gas (CO₂ in this case) to estimate the heat transfer rate is called mass transfer analogy and is explained and justified in detail in the next section.

1.3 MASS-TRANSFER ANALOGY AND OXYGEN SENSITIVE PAINT FOR FILM EFFECTIVENESS MEASUREMENT

1.3.1 THE HEAT AND MASS TRANSFER ANALOGY

In the event that two or more mechanisms are administered by dimensionless mathematical forms of the same type, the mechanisms are called analogous.

Figure 13 Thermal boundary layer development on an isothermal flat plate [39] assuming $(T_s - T_\infty)$ is constant

For instance, Figure 13 describes the thermal boundary layer over a flat plate. Where T_∞ is the mainstream temperature, u_∞ is the mainstream velocity, T is the local temperature, T_s is the surface temperature, δ_t is the thermal boundary layer thickness and $\delta_t(x)$ is the thermal boundary layer thickness as a function of distance. At the surface since there is no heat transfer due to the bulk of the fluid and the only heat transfer mechanism is through conduction, Newton's law of cooling is used to describe heat transfer at the surface. Newton's law of cooling is expressed as:

$$q''_s = h(T_s - T_\infty) \quad \text{Eq. 1.6}$$

Applying Fourier's law to the fluid at the surface yields:

$$q''_s = -k_f \frac{\partial T}{\partial y} \Big|_{y=0} \quad \text{Eq. 1.7}$$

Where k_f is the fluid conductivity at the surface. The heat transfer coefficient at the surface can be re-stated by combining the Fourier's law and Newton's law of cooling:

$$h = \frac{-k_f \frac{\partial T}{\partial y} \Big|_{y=0}}{T_s - T_\infty} \quad \text{Eq. 1.8}$$

Therefore, since $(T_s - T_\infty)$ is assumed to be constant, $\partial T / \partial y|_{y=0}$ is the strong driver on how the heat transfer coefficient is influenced across the thermal boundary layer. The magnitude of $\partial T / \partial y|_{y=0}$ decreases with the increase in x since the thermal boundary layer grows with the increase in x . in other words, the constant temperature difference that is represented by $(T_s - T_\infty)$ is spread out over a thicker thermal boundary layer (larger Δy) with the increase in x which makes the temperature gradient decrease in value. This results in the decrease of q''_s and h with the increase in x .

To assess the similarity between heat and mass transfer boundary layers, we shall take a look at the mass transfer boundary layer.

Figure 14 species concentration boundary layer development over a flat plate from [39] assuming constant $(C_{A,s} - C_{A,\infty})$

In Figure 14 the concentration boundary layer is illustrated. This is similar to air passing over dry ice where the process of sublimation (solid to gaseous phase transition) increases the concentration of CO_2 in the air current (C_A). The air current also has minute concentration of CO_2 ($C_{A,\infty}$) before meeting the plate. For this physical model we shall assume constant $(C_{A,s} - C_{A,\infty})$. $C_{A,s}$ is the surface concentration of CO_2 and δ_c is the concentration boundary layer thickness. The concentration boundary layer is the fluidic region where the local concentration level is between $C_{A,\infty}$ and $C_{A,s}$. In other words a gradient in CO_2 concentration exists between the surface of the dry ice plate and the mainstream air current. This gradient region is called the concentration boundary layer and is mathematically similar to the thermal boundary layer and velocity boundary layer. This concentration boundary layer is defined similar to the velocity boundary layer in which the δ_c value is determined based on the value of y coordinate in which the following relation becomes true for a given x coordinate:

$$\frac{C_{A,s} - C_A}{C_{A,s} - C_{A,\infty}} = 0.99 \quad \text{Eq. 1.9}$$

The CO₂ molar flux at the surface ($y = 0$) by diffusion in units of kmol/s.ft² can be determined based on an expression that is analogous to Fourier's law, and it is called Fick's law:

$$N''_{A,s} = -D_{AB} \frac{\partial C_A}{\partial y} \Big|_{y=0} \quad \text{Eq. 1.10}$$

The form of Eq. 1.10 is an approximation of a more general form of Fick's law of diffusion and is valid when the total molar concentration of the mixture ($C = C_A + C_B$) does not change. The variable D_{AB} is the binary diffusion coefficient and is the property of the binary mixture. Also analogous to Newton's law of cooling an expression that relates the molar flux to the differences in concentration variation across the boundary layer can be written as:

$$N''_{A,s} = h_m (C_{A,s} - C_{A,\infty}) \quad \text{Eq. 1.11}$$

Where h_m is the convective mass diffusivity. To write h_m in terms of mass diffusivity and concentration gradient, Eq. 1.10 and Eq. 1.11 can be combined to arrive at the following:

$$h_m = \frac{-D_{AB} \partial C_A / \partial y|_{y=0}}{C_{A,s} - C_{A,\infty}} \quad \text{Eq. 1.12}$$

The concentration boundary layer affects the concentration gradient at the surface ($\partial C_A / \partial y|_{y=0}$). This then affects the convective mass diffusivity and is then influential in the rate of species transfer in the boundary layer.

So far it has been established that the convective heat transfer at the surface is strongly dependent on its boundary layer thickness (δ_t) and similarly convective mass transfer is strongly dependent on its boundary layer thickness (δ_c).

Convective heat and mass transfers are identical when the Lewis number (Le), the ratio of thermal diffusivity to the mass diffusivity of the flow, is 1.

$$Le = \frac{\delta_t}{\delta_c} = \frac{\text{thermal diffusivity}}{\text{binary mass diffusivity}} = \frac{Sc}{Pr} \quad \text{Eq. 1.13}$$

Where Sc is the Schmidt number and is a ratio of the momentum and mass diffusivities and Pr is the Prandtl number and is the ratio of the momentum and thermal diffusivities. To understand the experimental results presented in the later segments, Nusselt number (Nu) and Sherwood number (Sh) need to be defined. These definitions can then be used to relate to Lewis number. It will be shown that the Lewis number is close to unity for laminar and turbulent flows.

Nusselt number is in essence the dimensionless temperature gradient at the surface. where the dimensionless temperature T^* and height y^* are defined as:

$$y^* = \frac{y}{L} \text{ \& } T^* = \frac{T - T_s}{T_\infty - T_s} \quad \text{Eq. 1.14}$$

Using parameters in Eq. 1.14, Nu provides a measure of convection heat transfer at the surface and can be written as:

$$Nu = \frac{\partial T^*}{\partial y^*} \big|_{y^*=0} = \frac{hL}{k_f} \quad \text{Eq. 1.15}$$

Similarly, the Sherwood number (Sh) can be thought of as the dimensionless mass concentration gradient at the surface and is a measure of convection mass transfer at the surface:

$$Sh = \frac{\partial C_A^*}{\partial y^*} \big|_{y^*=0} = \frac{h_m L}{D_{AB}} \quad \text{Eq. 1.16}$$

Using the analogy between the convective heat and mass transfer and Eq. 1.13, it can be established that:

$$\begin{aligned} \frac{Nu}{Pr^n} &= \frac{Sh}{Sc^n} \\ \frac{Sc^n}{Pr^n} &= \frac{Sh}{Nu} = Le^n = \frac{\delta_t}{\delta_c} \end{aligned} \quad \text{Eq. 1.17}$$

Goldstein et al. [40] showed that for a square cylinder the ratio of Sh to Nu is close to unity. This is illustrated in Figure 15. It can be deduced that the thermal and concentration boundary layers are therefore similar in this case.

Figure 15 Comparison of average mass transfer rates on the square cylinder with heat transfer measurements in the two dimensional flow region from [40].

In Figure 16 a similar comparison is made between convective heat and mass transfer analogies on a circular cylinder. The dotted line represents the corrected convective heat transfer where the conduction effect has been taken into account.

Figure 16 Comparison of heat and mass transfer on the circular cylinder in the two-dimensional flow region from [40].

Figure 17 Results for effectiveness η versus distance X/D downstream from a single row of 30° holes of diameter D . Carbon dioxide and air injection results for the same density ratios from [41].

Jones [41] showed that for a 30° round hole in a turbulent flow regime the effectiveness values for the mass transfer case are close to that of the heat transfer case. This allows the use of mass transfer over an impermeable wall as an analogue for heat transfer over an adiabatic wall.

For turbulent gaseous flows the Lewis number has been found to be approximately one [41] and therefore it is assumed to be close to 1 for the present study. It can then be assumed that the changes in the thermal and species distributions progress at similar rates. This makes the introduction of a more dense gas into a less dense gas a workable substitute for introducing cool gas into hot gas where both coolant and outer flow are similar as in the case of cold air injected into hot vitiated air in a gas turbine. Here CO₂ is injected into air resulting in a density ratio of 1.5.

Historically mass-transfer analogy testing for film cooling applications has relied on a gas sampling technique, where small holes, similar to pressure ports are drilled into the model, and samples of gas are extracted through these ports and chemically analyzed to determine the concentration, C_f , of the film. The film cooling effectiveness is then calculated by [42]:

$$\eta = \frac{T_\infty - T_f}{T_\infty - T_c} \cong \frac{C_\infty - C_f}{C_\infty - C_c} \quad \text{Eq. 1.18}$$

Where C_c and C_∞ are the mass concentrations of the coolant gas injected through the cooling holes, and the outer flow concentration, respectively. Each concentration term can be calculated by employing the equation below [42]:

$$C_i = X_{CO_2_i} \frac{W_{CO_2}}{W_i} \quad \text{Eq. 1.19}$$

Where $X_{CO_2_i}$ is the molar fraction of CO₂ equivalent to CO₂ volume percent, i denotes the fluid region (mainstream, coolant or mixture), W_{CO_2} is the molecular weight of CO₂ and W_i is the molecular weight of the fluid. The use of sampling taps is disadvantageous on two counts. Building taps into a test article is time consuming and expensive and makes the test article design

more complex. The limited number of taps yields poor spatial resolution of the measurement of film cooling effectiveness. Both of these shortcomings can be avoided by measuring gas concentration at the surface using Oxygen Sensitive Paint (OSP).

1.3.2 OXYGEN SENSITIVE PAINT

OSP is marketed as Pressure Sensitive Paint (PSP). It is a paint containing oxygen sensitive fluorescent molecules, luminophores, suspended in an oxygen permeable binder.

To appreciate the mechanism of luminescence and develop an understanding of the OSP measurement technique, it is important to introduce the Jablonsky energy-level diagram shown in Figure 18. This diagram outlines the energy level of the luminophore (a molecule that emits a different wavelength of light than the excitation wavelength) after being excited by an excitation photon and its possible relaxation pathways back to the stable ground state.

Figure 18 Jablonsky energy-level diagram with possible luminophore pathways 1) Initial excitation 2) Fluorescence 3) Phosphorescence

In Figure 18 the Y axis outlines the energy level of the luminophore. In process 1 an excitation photon is absorbed by the luminophore and its energy level elevated. Then the luminophore transitions into process 2 where it loses its energy by vibrational relaxation (internal conversion) until it drops to the level outlined by the thick horizontal line. This is called the semi-stable energy level. Shortly after, the luminophore's energy level jumps to the ground state and a photon is emitted as a result. Some luminophores of process 2 will jump from this semi-stable energy level. Through a less probable intersystem crossing some luminophores will cross into what is known as the forbidden spin state where the electrons within the same orbit are no longer spinning in the opposite direction but rather spinning in the same polarity direction which makes them repel the spin induced electric charge from one another. Crossing into this state places the luminophore at a lower energy level. This state is called the triplet state (process 3 in Figure 18). Luminophores can cross between the triplet state and process 2 (known as the singlet state) multiple times before emitting a photon. A luminophore in the triplet state loses its energy through vibrational relaxation in a similar fashion to the singlet state, then it reaches the triplet state semi-stable energy level where it then jumps to the ground level emitting a photon. Phosphorescence takes place when a photon is emitted while the luminophore had been in the triplet state. Phosphorescence is much slower than fluorescence. The combination of phosphorescence and fluorescence is called luminescence. Luminescence is a radiative method in which the luminophore relaxes to the ground state from the excited state.

Non radiative processes by which the OSP luminophore can relax include thermal energy transfer and collision with an oxygen molecule. At higher temperatures the number of luminophores that lose all of their energy due to internal conversion increases. The OSP excited luminophores interact with oxygen molecules in a non-radiative process or simply stated, O₂

molecules quench the luminescent emission (external conversion). Emission intensity of the excited luminescent molecules is inversely proportional to the collision frequency with the O₂ molecules. The collision frequency depends on O₂% volume or the partial pressure of O₂ and the temperature of the gas that contains O₂ molecules.

To account for the temperature dependence a second luminophore is included (marked as reference) in the paint, which does not relax from the excited state with O₂ collision. Figure 19 shows the reference component can be used to compensate for temperature dependency because its relative emission intensity does not change with the change in partial pressure of oxygen, but its temperature varies with the variation in temperature.

Figure 19 OSP emission spectra at different pressures and constant temperature (left) OSP emission spectra at constant pressure and different temperatures (right) from [43], excitation wavelength is 400 nm

In the presence of foreign gas where oxygen is deprived from the OSP surface, the intensity of the oxygen sensitive luminophore increases. To account for the foreign gas concentration increase (e.g. CO₂ injection through film cooling holes) from a reference condition (air injection through film holes), Henry's law is employed. A specific form of Henry's law is the Stren-Volmer equation:

$$\frac{I_{ref}}{I} = A(T) + B(T) \frac{X_{CO_2}}{X_{CO_2,ref}} \quad \text{Eq. 1.20}$$

In Eq. 1.20, I_{ref} is the intensity recorded from the reference condition (air injection), I is the recorded intensity from the test condition (CO_2 injection), $A(T)$ and $B(T)$ are the temperature dependent Stren-Volmer constants, X_{CO_2} is the CO_2 molar fraction at the test condition and $X_{CO_2,ref}$ is the CO_2 molar fraction at the reference condition. The Stern-Volmer equation can be expanded to bi-quadratic form and re-written where it can be employed in a more practical form [44]:

$$CO_2(I/I_r, T) = A + B(I_r/I) + C(I_r/I)^2 + T(D + E(I_r/I) + F(I_r/I)^2) + T^2(H + J(I_r/I) + K(I_r/I)^2) \quad \text{Eq. 1.21}$$

Constants $A, B, C, \dots$ are temperature independent constants determined from calibration by discreet CO_2 gas sampling calibration, T is the OSP surface temperature and (I_r/I) is the intensity ratio that is temperature compensated. Temperature compensation of the intensity ratio is achieved by dividing the intensity ratio from the temperature sensitive luminophore by the oxygen sensitive luminophore. A fellfield molar concentration of CO_2 can be calculated and Eq. 1.18 & Eq. 1.19 can be used to arrive at the effectiveness values. In a typical application of the technique, Narzary et al. [45] found an over-all uncertainty of 3%.

1.4 DISCHARGE COEFFICIENT AND SHAPED FILM COOLING HOLES

The ratio of actual mass flow rate to the ideal mass flow rate is called the discharge coefficient (C_D). To develop an understanding of the significance of discharge coefficient, it is

important to realize how it is derived and what fundamental equations are used to derive this.
Let's consider an orifice flow field (Figure 20).

Figure 20 Orifice flow streamlines.

In this flow field, there are laminar and separated flow areas. For the ideal flow rate where no compressibility and flow separation is assumed, Bernoulli's energy balance equation can be applied to balance the energy contained in the fluid at the upstream and downstream of the orifice plate:

$$P_1 + \frac{1}{2}\rho_1 V_1^2 + \rho_1 g h_1 = P_2 + \frac{1}{2}\rho_2 V_2^2 + \rho_2 g h_2 \quad \text{Eq. 1.22}$$

$\rho_1 = \rho_2 = \rho$ since the flow is assumed to be incompressible, $\rho_1 g h_1 - \rho_2 g h_2 = 0$, due to negligible height difference and it is assumed that the flow is at rest in the upstream region so $V_1 = 0$. An expression for V_2 in terms of the pressure difference (ΔP) and fluid density can be derived:

$$P_1 = P_2 + \frac{1}{2}\rho V_2^2$$

$$\frac{2(P_1 - P_2)}{\rho} = V_2^2$$

$$\sqrt{\frac{2(\Delta P)}{\rho}} = V_2 \quad \text{Eq. 1.23}$$

Mass flow rate at the downstream region can be written in terms of V_2 and A_{e2} . Where A_{e2} is the effective area and is defined as the cross sectional area which ideal frictionless flow would pass at a restriction between a large upstream reservoir and a large downstream reservoir. However, A_{e2} is unknown. The actual flow rate ($\dot{m}$) can be compared to the slug / ideal / effective flow rate ($\dot{m}_e$). In the ideal flow case ($\dot{m}_e$) the effective area which is the stream tube area (A_{e2}) can be assumed to be the geometric area A_2 .

$$\begin{aligned} \dot{m}_e &= \rho V_2 A_2 \\ &= \rho \sqrt{\frac{2(\Delta P)}{\rho}} A_2 \\ &= \sqrt{2\rho(\Delta P)} A_2 \end{aligned} \quad \text{Eq. 1.24}$$

Discharge coefficient can be written as the ratio of the actual mass flow rate ($\dot{m}$) to the effective/ideal mass flow rate ($\dot{m}_e$):

$$\begin{aligned} C_D &= \frac{\dot{m}}{\dot{m}_e} \\ &= \frac{\dot{m}}{\sqrt{2\rho(\Delta P)} A_2} \end{aligned} \quad \text{Eq. 1.25}$$

For fan shaped film cooling holes, Eq. 1.25 can be written as the ratio of geometrical area over the effective area as shown by Gritsch et al. [46]:

$$C_D = \frac{m_c}{P_{0c} \left(\frac{P_{\infty}}{P_{0c}}\right)^{\gamma+1/2\gamma} \sqrt{\frac{2\gamma}{(\gamma-1)RT_{0c}} \left(\left(\frac{P_{0c}}{P_{\infty}}\right)^{\gamma-1/\gamma} - 1\right) \frac{\pi}{4} D^2}} \quad \text{Eq. 1.26}$$

Where P_{0c} and P_{∞} are the coolant plenum and mainstream pressures respectively, T_{0c} is the coolant plenum temperature, m_c is the coolant flow rate, R is the specific coolant gas constant, γ is the ratio of specific heats and D is the film hole diameter.

Discharge coefficients for variety of mainstream Mach numbers and pressure ratios were presented by Gritsch et al. [46]. Shown in Figure 21, the increase in mainstream Mach number causes a decrease in discharge coefficient for a given pressure ratio. The findings concluded that the performance of the fan shaped and the laidback fan shaped holes investigated were similar. At low coolant to mainstream pressure ratios, high mainstream Mach numbers cause significant reduction in discharge coefficient values. High coolant to mainstream pressure ratios cause diffuser jet separation and a drop in discharge coefficients.

Figure 21 Discharge coefficients vs pressure ratios for various mainstream Mach numbers for a fan shaped hole (left) and a laidback fan shaped hole (right) at coolant Mach number of 0.0 from [46]

The diffuser sections of the film cooling holes tested by Gritsch et al. [46] have best operability in the low pressure ratio region which results in high pressure recovery and high

discharge coefficients. When the pressure ratios are higher, the coolant flow separates from the diffuser walls. As a result, pressure recovery is reduced and ultimately a decrease in discharge coefficient occurs [46].

1.5 THE EFFECT OF SURFACE ROUGHNESS ON FILM COOLING EFFECTIVENESS

During gas turbine operation the turbine blade and vane surfaces become rough. This is because of the erosion, spallation and deposition as illustrated in Figure 22.

Figure 22 Micrograph showing roughness caused by deposits of foreign materials along the surface and in a film cooling hole from [47]

Figure 23 shows that for increased roughness the Stanton number (a dimensionless parameter relating heat transfer coefficient to heat capacity of the fluid) increases.

Figure 23 Stanton number versus distance with low free-stream turbulence from [47]

Previous works on surface roughness done by Bogard et al. [47] and Rutledge et al. [48], though limited to their narrow set of test conditions, revealed that a rougher airfoil surface will lead to early boundary layer transition making it thicker which results in turbulent mixing in the boundary layer. Shown in Figure 24 it can be seen that the rougher configuration (gray) have lower effectiveness values at BR's of 0.3 and 0.7. However, at BR of 1.4 the rougher configuration has significantly higher effectiveness. The roughness (R_a) added to the smooth case was $0.12D$ where D is the film cooling hole diameter.

**Figure 24 Spanwise averaged comparison of adiabatic effectiveness.
Smooth and all rough under high mainstream turbulence intensity
for a suction side turbine blade from [48]; added $Ra = 0.12D$**

These changes at lower BR's will cause a decrease in film cooling effectiveness while at high blowing ratios a rise in film cooling effectiveness can be identified. They also found that roughness upstream of the film holes caused as much as 25% drop in spatially averaged film cooling effectiveness. Goldstein et al. [49] and Schmidt et al. [50] studied changes in heat transfer coefficient that a row of holes on a flat surface would present. The roughness downstream of the film holes was found to have little effect on span averaged film effectiveness.

1.6 THE EFFECT OF INTERIOR ROUGHNESS ON DIFFUSER PERFORMANCE

Since the geometry under investigation is of a diffuser shaped hole, understanding of diffuser flow dynamics with relation to roughness is critical in explaining some of the resulting flow features. Persh et al. [51] studied the influence of surface roughness on pressure recovery in a 23° conical diffuser. Their findings are shown in Figure 25 with the roughness configurations outlined in Figure 26. The rough segments had the roughness to diameter ratio (Ra/D) of 0.005.

Figure 25 Boundary-layer velocity profiles at diffuser exit, station 6, for all configurations from [51]

Figure 26 Cross section of diffuser wall showing various surface-roughness dimensions relative to diffuser inlet from [51].

The findings concluded that surface roughness slightly upstream of the diffuser throat stabilizes the resulting flow downstream and prevents flow separation. This is of significance because it foretells that the surface roughness of the throat is an influencing parameter in downstream behavior of a diffuser. They also showed that in a separated diffuser exit velocity profile (asymmetrical profile) the increase of surface roughness near the diffuser throat caused the diffuser outlet velocity profile to become more uniform (symmetrical) compared to that of the smoother case. In other words, the increase of surface roughness near the diffuser throat improved diffuser performance and prevented flow separation.

1.7 ADDITIVE MANUFACTURING (3D PRINTING)

Three printing technologies are compared in the present study along with several build layer thicknesses. There are several parameters within any 3D printing process that will influence the quality and geometric fidelity of the produced part. Additive manufacturing builds up a part layer by layer, and the build layer thickness is the parameter with the largest influence on the geometric fidelity [52, 53]. This parameter has a greater influence on the part quality than road width or print speed. These 3D printed processes are compared to a test piece that is CNC machined from a block of aluminum capable of 1-mil profile tolerances. This represents the

baseline case against which the 3D printed cases are compared to. Finally, to assess the film flow quality and geometric quality of the different types of additive manufacturing processes, the results are compared to the aluminum coupon. As shown in Figure 27 the aluminum coupon is manufactured to the same dimensions with the CNC machining method. While the aluminum coupon shows clean and sharp definition in the quality of the film hole shapes especially around the edges, the SLA coupon show visible deviations from the intended design.

Figure 27 Close-up view of geometric quality for aluminum (top) and SLA (bottom)

1.7.1 ADDITIVE MANUFACTURING TECHNOLOGIES

For laboratory testing there is now an alternative to slow and expensive machining of the complex hole shapes used for film cooling, allowing more geometries to be tested more quickly. Additive Manufacturing (AM), known more generically as 3D printing allows the rapid production of complex geometries. A solid model of any shape can be rendered in resin, metal or plastic in hours or minutes. Figure 28 shows that when machining a part in a traditional method, complexity and customization can lead to higher cost. With AM the cost per part stays constant and is no longer a function of complexity/customization [54].

Figure 28 complexity vs cost per part for additive manufacturing and traditional machining from [54]

The first 3D printing technology employed is Stereo Lithography Apparatus (SLA) in which a liquid resin is hardened by a laser into a semitransparent solid. The final part is then placed in a UV curing oven for post curing. This process is used to produce test pieces with build layer thickness of 20 μm . schematics of the SLA AM technique is illustrated Figure 29.

Figure 29 SLA 3D printing technique

The second process is the Fused Deposition Modeling (FDM) technique which has been one of the most widely used 3D printing technique due to its low cost and simple operation. The schematic of a typical FDM 3D printer is illustrated in Figure 30.

Figure 30 Fused Deposition Modeling (FDM) schematic

The build platform is heated and regulated to a specific temperature in order to keep the part from sliding and minimize deformation due to temperature change. Two-dimensional build layers are added up on the build platform to create a precise 3D part. The extrusion nozzle is heated to the melting point of the deposited material. The nozzle and filament extruder assembly move in X and Y directions while the heated build platform moves in the Z direction. The filament extruder pushes the filament through the heated nozzle to deposit the build material into its designated location. For overhangs where support is required, a porous and easily removable block is built underneath the overhang using the same filament material as the part itself. No post curing is needed for the FDM parts.

The third process is the PolyJet® process, a subfamily of Stereolithography (SL) prototype production is outlined in Figure 31.

Figure 31 PolyJet® 3D printing schematic

PolyJet® printing technique is much like the FDM process. The only major differences are the way the build material is deposited and the support material construction. The build material is a UV curable photopolymer resin that the inkjet nozzle deposits on the part surface. The deposited material is then immediately cured using UV light. Where support material is required, a gel-like substance is deposited that is removable using water. No post curing is needed for the PolyJet® parts.

1.7.2 ADDITIVE MANUFACTURING AND SURFACE ROUGHNESS

So far it has been shown that the nature of the AM is essentially stacking build layers with some thickness. Because of this the surface quality of the parts manufactured using AM is generally inferior to that of CNC machining. This is called the stair stepping effect and is shown in Figure 32.

Figure 32 Stair-stepping effect in AM (a) CAD model, (b) AM part, and (c) surface profile schematic from [55]

Generally the finer/thinner the build layer is, the closer the surface quality becomes to the CNC machined part. Kim et al. [56] designed and built the specimen outlined in Figure 33 to measure roughness on inclined surfaces at various angles using various AM technologies.

Figure 33 Specimen for measuring the roughness of inclined surfaces (50mm by 100mm by 45mm) from [56]

Figure 34 shows the measured surface roughness values for each AM technique investigated. Across almost all of the plotted roughness values, the 30° surface inclination seems to have the highest roughness. This is because the stair stepping effect is most pronounced at this build angle. Figure 35 shows the surface profilometry for the build angle of 30°. The FDM process appears to cause jagged surface quality ($\Delta y = 200 \mu\text{m}$) while the PolyJet ($\Delta y \sim 6 \mu\text{m}$) and SLA ($\Delta y \sim 20 \mu\text{m}$) parts have a smoother surface. For parts manufactured using SLA and the

PolyJet technologies, 0° surface build angle was the smoothest, while for the FDM the 90° build angle was the smoothest for that technique.

Figure 34 Variations of surface roughness according to build angles and AM technology from [56].

By looking at SL (also known as SLA) techniques, the surface roughness of the 90° build angle is always lower than that of the 60° build angle. The same relationship can be observed for the FDM part. For the PolyJet the mentioned relation is inverted meaning that the 90° build angle is much rougher than that of the 60° build angle.

Figure 35 Stair-stepping profiles of surfaces with build angle of 30° from [56].

CHAPTER 2: EXPERIMENTAL APPROACH

2.1 GOOMETRIES TESTED

Aside from variations produced by the different manufacturing techniques, the hole geometries in all cases was the same. The geometry tested is a scaled version of the geometry used by Schroeder et al. [2]. The fan-shaped laid-back holes have a 7° layback angle and a 7° side angle on each side so they are referred to as 7-7-7. The details of the geometry that was tested by Schroeder et al. [2] is shown in Figure 36 with the dimensions outlined in Table 4.

Figure 36 Baseline shaped hole design from [2].

Table 4 Geometric Parameters for Baseline Shaped Hole from [2]

	Range Common in Literature	7-7-7 Shaped Hole
Diameter, D (mm)	0.5 - 10	7.75
Injection Angle, α	30 to 55°	30°
L_m/D	1 to 4	2.5
L_{lat}/D , L_{fwd}/D	1.6 to 9.5	3.5
L/D	2.8 to 11.5	6
Laidback Angle, β_{fwd}	2 to 25°	7°
Lateral Angle, β_{lat}	2 to 18°	7°
P/D	2.8 to 8	6
Coverage Ratio, t/P	0.3 to 0.8	0.35
Area Ratio, AR	2.5 to 4.7	2.5
Sharpness of Inlet and Breakout Edges	Usually Sharp	Sharp
Rounding of Four Edges Inside Diffuser, R/D	0 to 0.5	0.5

The film hole dimensions for the current study are shown in Figure 37.

Figure 37 7-7-7 hole geometry used in the present study, dimensions in inches [mm]

An array of 7 holes is used giving good periodic behavior among the center holes which are well away from end wall effects. Film hole diameter (D) was 2.54 mm (0.10 in) for all cases.

The holes are spaced $6D$ apart. One test coupon was manufactured by traditional CNC machining from Aluminum. This high-precision process achieves profile tolerances under $40\text{ }\mu\text{m}$ (0.001 inch). The additively manufactured hole geometries are identical except for the roughness introduced by each of the 3D printing techniques, so any variation in film cooling effectiveness will be the result of the imperfections introduced by the differing build layer heights. This hole geometry was constructed by four techniques using build layer thicknesses from $0.001D$ ($25\text{ }\mu\text{m}$) to $0.12D$ ($300\text{ }\mu\text{m}$) as well as traditional machined metal. Each AM coupon along with the CNC aluminum coupon is shown in Figure 38.

**Figure 38 Close-up view of geometric quality for each processed coupon,
(a) CNC Aluminum Coupon, (b) SLA Coupon, (c) PolyJet Coupon,
(d-f) FDM Coupons 200-250-300 μ layer resolutions**

While the aluminum coupon shows clean and sharp definition in the quality of the film hole shapes, the plastic coupons show visible deviations from the intended design. Film hole diameters for all coupons were kept constant at 0.1 inches. In a report discussing high pressure turbine test hardware prepared for NASA [38], actual engine film holes sizes ranged from 0.020 to 0.024 inches which makes the holes sizes for the current study to range between 4.16 to 5 times larger.

Table 5 lists the cases studied, the manufacturing technology, the material, build layer thickness and the surface roughness values to be discusses in section 2.6. The aluminum CNC machined coupon has the lowest roughness on unpainted surfaces (inside the holes) with the SLA coupon being the second.

Table 5 Test coupons produced with measured roughness values and observed film lift of BR's

Layer thickness (μm)	Manufacturing Technique (qty.)	Material	Roughness Ra/D	Observed Liftoff (BR)
N/A	CNC (1)	Bare Al	0.00038	2.5
		Painted Al	0.00650	
25 (0.010D)	PolyJet (3)	RGD525	0.00927	2.0
25 (0.010D)	SLA (1)	Photo-polymer	0.00545	2.0
200 (0.08D)	FDM (1)	ABS Plastic	0.00896	>3.5
250 (0.10D)	FDM (1)	ABS Plastic	0.01077	3.0
300 (0.12D)	FDM (1)	ABS Plastic	0.01288	3.5

2.2 WIND TUNNEL AND GAS SUPPLIES

2.2.1 GAS SUPPLY SYSTEM

Figure 39 Experimental Arrangement, red indicates CO2 flow while black indicates air flow

The air and gas supply system is shown schematically in Figure 39. Air is compressed, dried and stored at a 160 (low pressure system) or 1500 psig (high pressure system) tanks. The facility has the capability to employ either system as outlined in Figure 40.

Figure 40 Upstream of the supply metering system outlining each component

Figure 41 Downstream of the supply metering system outlining each component

It is passed through a shutoff valve and a regulating valve which is used to control the pressure supplied to a sonic metering nozzle. So long as the pressure is sufficient to choke the nozzle, the mass flow supplied to the experiment is steady and is controlled by the pressure and temperature upstream of the sonic nozzle. The choked density and velocity (ρ^*_{air} , a^*_{air}) can be calculated using the isentropic relations from $P_{1,\text{air}}$ (0-150 psig transducer) and $T_{1,\text{air}}$ (Type K thermocouple). The mass flow can then be determined from these and the nozzle area, A^*_{air} , given by the nozzle manufacturer (Flowmaxx Engineering). The formula provided by the manufacturer to calculate the mass flow rate (lb_m/s) is presented in Eq. 2.1.

$$\dot{m} = \left(a + bP_1 + \frac{c}{\sqrt{P_1}} \right) \frac{P_1}{\sqrt{T_1}} \quad \text{Eq. 2.1}$$

Where P_1 and T_1 are the sonic nozzle upstream pressure (psia) and temperature ($^{\circ}\text{R}$) respectively, a , b and c are dimensionless coefficients provided by the manufacturer and vary for each sonic nozzle throat diameter. These coefficients along with sonic nozzle throat sizes are outlined in Table 6.

Table 6 Sonic nozzle throat sizes along with coefficients for mass flow calculations

	Throat Diameter (inches)	a	b	c
Air Supply	1.2518	6.7893751E-01	2.4561922E-05	-5.9804948E-03
Coolant Supply	0.125	7.7579966E-03	1.4586841E-06	-1.1098944E-04

The downstream pressure $P_{2,\text{air}}$ (0-250 psig transducer) is monitored to verify that the nozzle remains choked. The sonic nozzle is choked when the ratio of P_1 to P_2 is greater than 1.2. After flow metering, the air passes into a settling chamber with an area 125 times the test section area. Honeycomb flow straightening and a perforated plate are installed within the settling chamber to align the flow and ensure uniformity and reduced turbulence before the chamber

pressure $P_{0,\text{air}}$ (0-150 psig transducer) and $T_{0,\text{air}}$ (type K thermocouple) are measured as outlined in Figure 42. The flow then enters a 4 by 1.5 inches test section through a bell-mouth nozzle.

Figure 42 Air plenum with pressure and temperature measurement locations outlined

Liquid CO_2 is stored in a 1000 liter tank. It passes through a vaporizer and several hundred feet of piping, delivering it at approximately room temperature to a shutoff valve and a pressure regulator which is used to control the pressure supplied to a sonic metering nozzle. So long as the pressure is sufficient to choke the nozzle, the mass flow supplied to the experiment is steady and controlled by the pressure and temperature upstream of the sonic nozzle. The choked density and velocity ($\rho^*_{\text{CO}_2}$, $a^*_{\text{CO}_2}$) can be calculated from the isentropic relations from P_{1,CO_2} (0-130 psig transducer) and T_{1,CO_2} (type K thermocouple). The mass flow can be determined from these and the nozzle area, $A^*_{\text{CO}_2}$, given by the nozzle manufacturer. The downstream pressure P_{2,CO_2} (0-250 psig transducer) is monitored to verify that the nozzle remains choked.

The CO₂ is then passed through the settling chamber with an area of nearly 150 times the area of the metering holes in the test coupon. The CO₂ flow enters the chamber through 4 inlets creating a vortex that is parallel to the test coupon. The flow is then passed through a perforated plate for further flow conditioning (Figure 43). The chamber pressure P_{0,CO_2} (0-130 psig transducer) and T_{0,CO_2} (type K thermocouple) are measured downstream of the flow settling components.

Figure 43 Coolant plenum schematic

A diverting valve can substitute compressed air for CO₂ upstream of the flow metering in order to pass air through the cooling holes instead of CO₂. This is done as part of the OSP measurement process and is described later.

The test section and plenums are enclosed in a light-tight room which is equipped with forced ventilation to prevent the accumulation of excess CO₂ in the laboratory. There is also a CO₂ detection sensor installed in the vicinity of the operator to ensure that the CO₂ volume

concentration levels are within safe limits as shown in Figure 44. An alarm goes off if the CO₂ volume concentration levels goes beyond 2000 parts per million. Safe levels, according to the Occupational Safety & Health Administration (OSHA), safe limits are below 5000 ppm.

Figure 44 CO₂ safety sensor showing CO₂ volume concentration levels in parts per million.

2.2.2 WIND TUNNEL

The test section is a rectangular 4.0 by 1.5 inches duct with clear acrylic side walls and top. The floor of the test section houses an interchangeable test coupon which includes the cooling holes and the first row of gas sampling ports. The material of this coupon varies depending on which 3D printing technique is tested. Downstream of this coupon, the floor consists of an aluminum plate with nine rows of four gas sampling taps. The gas sampling taps extend 52.5 hole diameters downstream of the pierce point of the cooling holes. Both the interchangeable test coupon and the aluminum floor with sampling taps are painted with OSP. The assembled test section with the CO₂ plenum is shown in Figure 45. It encloses test coupon of 5.5 inches long by 3.0 inches wide and 0.375 inches thick.

Figure 45 Detailed experimental dimensions with outlined axis convention. The dots represent gas sampling port locations. The test coupons are the parts manufactured by 3D printing and each contain a row of seven 7-7-7 cooling holes as well as the first row of gas sampling taps. ($D = 0.1$ inches)

For all contour plots, the film hole downstream edge, commonly referred to as the breakout point, was chosen to be the Y/D of zero and the centerline of the middle hole was the X/D of zero.

2.3 ADDITIVE MANUFACTURING

2.3.1 BUILD ORIENTATION

The build orientation for all AM coupons was kept the same. The build orientation was chosen in such way that the cylindrical sections of the holes were built completely vertically to prevent the stair stepping effect on the hole interior. The schematic of build orientation is shown in Figure 46.

Figure 46 AM build orientation for all test coupons, top surface was built at 60° build angle while the cylindrical portion of the film hole interior was built at 90° build angle.

2.3.2 MATERIALS AND TECHNOLOGIES

Table 7 shows the materials used for each technique along with the material property and the AM machine that made the parts. ABS is one of the most widely used and cheapest materials available while RGD 525 is quite expensive. The SLA coupon was provided by an organization outside of the University of Cincinnati and the information regarding its material and AM machine is to be kept confidential. The RGD 525 is stronger than the ABS plastic, but it has a lower glass transition temperature. For OSP application the glass transition temperature needs to be higher than 140° F. This is because the painted coupons need to be placed in an oven at the temperature of 140° F for 2 hours.

Table 7 AM material properties and machines used in the present study

	FDM	PolyJet
AM Machine	MakerBot Replicator 2	Objet260 Connex
Material	ABS Plastic	RGD 525
Tensile strength (psi)	4,700	10,000-11,500
Elongation at break (%)	6	10 - 15
Flexural Strength (psi)	8,450	16,000-19,000
Flexural Modulus (psi)	300,000	450,000-510,000
Glass Transition Temperature (°F)	226	144-149

A coupon made from PLA plastic was also manufactured which warped in the oven because its glass transition temperature was much lower. The PLA coupon and its warpage are shown in Figure 47.

Figure 47 Warpage in the PLA coupon after being subjected to 140° F for 2 hours

2.4 TEST COUPON SURFACE TOPOLOGY

The surface topology was measured using a Bruker Contour GT-K1 3D Optical Microscope.

Figure 48 Bruker Contour GT-K1 3D Optical Microscope

This device employs two light colors, green and white, for interferometry to measure 3D surface topology to sub-nanometer resolution. The device then calculates a surface roughness value over the measured region. A total scan area of $0.5D \times 0.5D$ was chosen immediately upstream of the middle film hole illustrated in Figure 49. The surface inside the hole was inaccessible to the microscope lens, due to its sloped surface. CT scanning, which would have examined the inside of the holes has a much larger resolution ($50\text{ }\mu\text{m}$ or 0.002 in) so a surface measurement was taken as most representative of the roughness over the whole part. The upstream region of the middle hole was chosen as a representative roughness value to represent the internal roughness. This relies on results from Kim et al. [56]. The roughness inspection location was chosen to be upstream of the film cooling holes instead of the downstream location because surface roughness upstream of the film holes can cause as much as a 25% decrease in spatially averaged film cooling effectiveness [47, 48].

Figure 49 Surface profilometry measurement location

Figure 50 Surface inclination with respect to build orientation

Kim et al. [56] designed a specimen that incorporated various inclinations from 10° to 90° to study the effect of various AM techniques on the surface roughness of the resulting parts with different build orientations. They investigated PolyJet, FDM and SLA technologies and reported that the surface roughness was generally higher for the techniques that utilized larger build layer thicknesses compared to finer build layer resolutions regardless of the surface inclination with the exception of PolyJet. By measuring the surface roughness of the same representative region of the test coupons, one can assume the relative internal roughness of the film cooling holes. Their results are compared to the current study in Figure 50.

For the AM coupons the surface roughness on the 60° build angle (surface roughness measurement location) can be related to the roughness on the 90° build angles surfaces (film hole interior). The rougher the measurement location is, the rougher the hole interior would be as outlined in Figure 50. This relation is inverted for the PolyJet coupon. The roughness values for the present study are higher due to the added roughness from OSP application.

The roughness of an unpainted portion of the aluminum coupon is shown in Figure 51. It can be assumed that the diffuser throat roughness will have a similar roughness value since the throats were not painted.

Figure 51 Unpainted CNC machined aluminum 3D roughness plot

Figure 52 shows that OSP can significantly change the height difference between the peaks and valleys on the part topology and therefore can change its roughness significantly.

Figure 52 Surface topology for various test coupons after OSP application with scan side length of 0.5D (50 mil)

2.5 GAS SAMPLING

Ten rows with four sampling taps each are connected to an array of VALCO Instruments EUTB-CSD16MWE multi-position valves (functionally similar to a classic Scanivalve) which connect one port at a time to a Siemens Ultramat 23 CO₂ gas analyzer. Figure 53 shows the schematic of how the sampling valves are connected. The home port of the first valve is connected to the last port of the second valve and the home port of the second valve is connected to the last port of the third valve. The third valve is connected to the gas analyzer through its home port. A LabVIEW code was written to control all valves through USB connection.

Figure 53 Gas analyzer and sampling valves arrangement

This gas analyzer measures the infrared absorption of a sample gas in order to determine the CO_2 concentration [57]. The infrared measurement technique relies on the infrared wavelength absorption bands. These bands are unique for each molecule. Figure 54 shows the details on how the gas analyzer measures the concentration of CO_2 . An infrared radiation source (7) operating at 600°C produces infrared radiation. This radiation is then modulated (5). The generated infrared radiation goes through the analyzer chamber (4) where the gas mixture from the experiment flows. The analyzer internal pump was set for sample gas flow rate of 1 liter per minute which would roughly be 10% of the mainstream velocity. The intensity of the infrared radiation is reduced with the increase in CO_2 concentration. The detector chamber has two or three layers of detection [(11), (2) and (12)] and is filled with the gas to be measured. These layers detect the IR from the central and outermost sections of the IR band. A pulsating flow is generated (5) and is converted to an electrical signal (3). A Wheatstone bridge is employed that uses this electric signal and converts it to a current output that is proportional to the CO_2 volume

percent. In addition to the sampling ports, gas from the CO₂ plenum and air plenum are sampled to ensure that contamination of either gas would be detected.

Figure 54 Operating principle of infrared measurement from [57]

A settling time study was performed in order to determine the minimum length of time each port should be sampled and how long after switching ports should be allowed before beginning to record concentrations values. Following switching between the air and CO₂ plenums, a settling time of three minutes was selected followed by one minute of data sampling which is then averaged. Figure 55 shows a typical gas concentration trace switching from the air plenum to the CO₂ plenum. Before each experiment the gas analyzer was calibrated using instrument grade nitrogen and CO₂ bottles to calibrate for 0% and 100% CO₂ concentrations respectively.

Figure 55 Typical gas analyzer concentration time trace

This implies that a given test, performed by gas sampling will take a minimum of 168 minutes. As a practical matter more time is needed to establish the set point and to ensure steady flow. This illustrates the point that gas sampling is time consuming, and OSP analysis can save time, increase spatial resolution and reduce manufacturing cost.

2.6 OXYGEN SENSITIVE PAINT TECHNIQUE

Han et al. [42] provided a detailed summary of the method, its application and calibration options for film cooling effectiveness. A Binary-FIB paint obtained from Innovative Scientific Solutions Incorporated (ISSI) is employed. The paint is sprayed onto a model surface using an airbrush outlined in Figure 56. After each application, the airbrush was disassembled and each component was soaked in acetone for approximately 2 minutes. Then each component was cleaned using appropriate brushes and paper towel. The most important part of the airbrush is its needle. If the needle is damaged or dirty, the paint application will produce inconsistent paint coverage and can introduce errors. The airbrush was connected to an airbrush compressor where the pressure was set to 20 psig.

Figure 56 Airbrush used for OSP application with its components

First an FIB Basecoat is applied on the test coupon. The basecoat covers scratches and stains and prevents model surfaces from fluorescing and interfering with OSP data. To minimize the illumination inaccuracy and intensify the OSP emission, a consistent reflective surface is needed. FIB basecoat can provide this uniform reflectivity. 40 ml of FIB basecoat was applied to each coupon. For the coupons that were not completely opaque such as the PolyJet and the SLA coupons, a coat of black airbrush paint was applied prior to the FIB basecoat application. This is to prevent an effect known as “haloing effect” to take place. The haloing effect produces error around the film cooling holes and induces effectiveness where it is not expected. The results with

and without haloing effect are shown in Figure 57. 40 ml of the opaque black paint was applied to the PolyJet and SLA coupons.

Figure 57 Haloing effect present (bottom), haloing effect eliminated (top)

The binary paint allows temperature-compensation to remove temperature dependence from the oxygen concentration measurement. The paint is marketed under BF-400. It has two luminophores; one that is sensitive to oxygen and temperature (emission at 650 nm) with the second luminophore being sensitive to only temperature (emission at 556 nm). The ratio of the two luminophores enables the isolation of the temperature effect from oxygen sensitivity. The temperature sensitive luminophore has to be cured in an oven for two hours at the temperature of 140-150 °F.

**Figure 58 Fundamentals of OSP operation (right [43])
OSP measurement in the present study (left)**

Figure 59 BF-400 binary OSP (a), FB-400 basecoat (b) and opaque black airbrush paint (c)

A 4 Watt 400nm LED and a 16 bit, 2 mega pixel color charge-coupled device (CCD) camera (PCO 1600C) with 530nm filter are employed. A color CCD camera has a Bayer filter over its CCD sensor, which is designed based on an RGB color model. Each group of four pixels has one red, one blue, and two green filters. For a two-color paint, the two separate emission signals can be recorded simultaneously using one color CCD camera, eliminating the need for a complicated optical setup, such as a filter wheel or two separate cameras. Camera exposure time was adjusted to 85% saturation limit for each geometry. A dark background image (dark image) is recorded and subtracted from each bright image to remove camera dark current and any light contamination that is not removed by the light-tight enclosure.

50 Images are collected and averaged when the injected coolant is air (CO_2 off) and when the coolant is CO_2 (CO_2 on). This allows for the calculation of film effectiveness by substituting the intensities from each image namely dark image, CO_2 on and CO_2 off into the equation as

defined by [42]. Blowing air through the holes for the CO₂ off case insures there is no significant change in surface pressure, so any change in partial pressure of O₂ will be due to changes CO₂ in concentration. A calibration process employs simultaneous gas sampling from a limited number of CO₂ gas sampling taps across a range of local intensities. The procedure is outlined in Figure 60. The local results from the CO₂ gas sampling ports are overlaid on the local OSP results validating the OSP method. Examples are shown in section 3.1.

Figure 60 OSP image processing procedure

2.7 TEST CONDITIONS

The mainstream flow was kept at a constant Mach number of 0.30 with Re_x of 897109, approach boundary layer thickness of 1.29D and the coolant temperature was kept within 5° R of the mainstream flow. Each coupon was subjected to the blowing ratios (BR) and the corresponding momentum flux ratios (I) shown in Table 8.

Table 8 Test conditions for each coupon with mainstream Mach of 0.3

BR	1.0	1.5	2.0	2.5	3.0	3.5
I	0.58	1.18	1.85	2.52	3.16	3.76

At blowing ratio of 1.0 gas sampling was performed simultaneously with the OSP technique to ensure that the OSP calibration is valid.

Table 9 Measured coolant mass flow rate for all cases

	BR →	1.0	1.5	2.0	2.5	3.0	3.5
CO₂ mass flow rate (lb_m/s) →	Aluminum	0.0106	0.0159	0.0212	0.0264	0.0317	0.0368
	SLA	0.0104	0.0157	0.0209	0.0260	0.0313	0.0364
	PolyJet	0.0106	0.0159	0.0211	0.0263	0.0316	0.0369
	FDM 200	0.0105	0.0158	0.0211	0.0263	0.0315	0.0365
	FDM 250	0.0105	0.0159	0.0211	0.0264	0.0316	0.0367
	FDM 300	0.0105	0.0158	0.0210	0.0263	0.0315	0.0366

The mainstream flow Reynolds number (897109) was calculated using mainstream mass flow rate, pressure and temperature and the calculation for arriving at the value is as follows:

$$P_{flow} = 14.38 \text{ psia}, T_{flow} = 513.18 \text{ }^{\circ}\text{R}, \mu = 3.82 \times 10^{-7} \left(\frac{\text{lb}_f \text{s}}{\text{ft}^2} \right), V = 333.72 \left(\frac{\text{ft}}{\text{s}} \right)$$

$$R = 1545.35 \left(\frac{\text{ft lb}_f}{^{\circ}\text{R lb}_{\text{mol}}} \right), \bar{m}_{air} = 28.89, L_{\text{film row to inlet}} = \frac{5.26}{12} \text{ ft}, \gamma = 1.4$$

$$R_{air} = 1545.35 / 28.89 = 53.49 \left(\frac{\text{ft lb}_f}{\text{lb}_m ^{\circ}\text{R}} \right)$$

$$\rho = \frac{P_{flow} \times 144}{R_{air} \times T_{flow}} = 0.0754 \left(\frac{\text{lb}_m}{\text{ft}^3} \right)$$

$$\nu = \frac{\mu}{\rho \times 32.2} = 1.63 \times 10^{-4} \text{ s}^{-2}$$

$$Re_x = \frac{V \times L_{\text{film row to inlet}}}{\nu} = 897,109 > 500,000 \Rightarrow \text{turbulent flow}$$

$$\delta = \frac{L_{\text{film row to inlet}} \times 0.38}{Re_x^{1/5}} = 0.129 \text{ in} = 1.29D$$

2.8 MEASUREMENT UNCERTAINTY

The data reported here contain measured values (i.e., pressure, and temperature) and calculated values (i.e., M_∞ , BR, etc.). For measurements pertaining to mainstream and coolant flow delivery (i.e., pressure transducers and thermocouples), the pressure and temperature vary by a maximum of ± 0.15 psi and $\pm 0.3^\circ\text{R}$, respectively. The contour optical microscope has a vertical resolution of 0.01 nm, lateral resolution of 0.01 μm , step height accuracy of 0.75% and step height repeatability of 0.1%. Linearized systematic error analysis presented by Moffat et al. [58] is used to calculate the uncertainty associated with calculated quantities and for the case of OSP derived film cooling effectiveness the procedure proposed by Mendoza [59] is used. The values for mainstream Mach can vary by a maximum 1%. Largest BR error is accumulated for the lowest coolant flow rates (0.6%). Largest coolant flow rate uncertainty is 0.5%. Discharge coefficient is calculated from the coolant plenum pressure ratio and mass flow rate and is found to vary up to 3%. Film cooling effectiveness is calculated based on the image intensity ratio of air as coolant vs CO_2 as coolant. The recorded emission intensity is related to a known CO_2 concentration (measured using gas sampling). Therefore, the main agents affecting the uncertainty of film cooling effectiveness are the uncertainty in the CO_2 concentration measurement and the intensity ratio measurements. The gas analyzer has the uncertainty of 0.04% (when calibrated with instrument quality gas) while the intensity ratio recorded by the CCD camera has the lowest signal to noise ratio of 25. The highest uncertainty is present where the CO_2 concentration is lowest. For film cooling effectiveness the highest uncertainty is 6.0% ($60 < Y/D < 80$) and the lowest is 2.5% ($-4 < Y/D < 10$). This maximum value of 6% is three times the maximum variation observed between PSP and gas analysis measurements (1.7%) and the instrumental limit of the gas analyzer (0.04%), so the overall measurement uncertainty in film

cooling effectiveness is dominated by optical noise. The overall measurement uncertainty in film cooling effectiveness is taken to be 6% which is comparable to values reported by Narzary et al. (3%) [45]. Three identical PolyJet coupons were manufactured, painted and subjected to identical flow conditions for repeatability evaluation.

Figure 61 OSP repeatability evaluation

Shown in Figure 61 the repeatability results are plotted. Repeatability appears to be acceptable on every BR except for the BR of 2.0. The 7-7-7 geometry was reported to show film lift off at BR of 2.0 by [2]. At the film lift off BR the manufacturing tolerance would play a more significant role in uncertainty. Overall the results show that the OSP technique is repeatable because the lack of repeatability is only seen at BR of 2.0 and not in a systematic fashion. Hot wire anemometry was performed at Mach number of 0.14 for turbulence intensity measurements. The Mach number of 0.14 was chosen to match the round hole validation study presented in 3.1. Turbulence intensity was 0.5%. The results are shown in Figure 62.

Figure 62 Hotwire anemometry results, (1) showing zoomed in plot for the low velocity fluctuation period, (2) showing zoomed in plot for the higher velocity fluctuation period

Velocity spikes are most likely due to pressure regulator diaphragm movements as it is adjusting its position to regulate the pressure. The results from hotwire anemometry were compared to the velocity calculation from the sonic nozzle flow metering and the comparison showed a good agreement.

Table 10 Hot wire anemometry to sonic nozzle comparison

	Sonic Nozzle	Hot Wire	% Difference
Mass Flow Rate (lbm/sec)	0.487	0.482	0.9%
Velocity (ft/sec)	157.5	155.8	1.1%

CHAPTER 3: RESULTS AND DISCUSSION

For each test coupon, film effectiveness contours determined by the OSP technique at each BR are plotted with the X and Y axes normalized by the hole diameter. Span average effectiveness is integrated over the center three holes to ensure that wall effects are minimized in the span effectiveness plots. In order to study the geometrical fidelity of each test coupon, plots for each hole per coupon at BR of 2.5 were produced and compared.

3.1 OSP VERIFICATION

For facility validation results from Baldauf et al. [60] was compared to a round hole coupon that was CNC machined from aluminum. The estimated boundary layer thickness for the current facility is 40% of the hole diameter based on the growth rate of a turbulent boundary layer over a flat plate. This value is 4 times larger than that of the compared test case from the literature. This difference in boundary layer thickness explains the lower peak film effectiveness value presented in the current study. Eriksen et al. [61] found that the thin approach boundary layer causes the coolant jet to encounter a greater “force” upon injection into the mainstream than in a thicker approach boundary layer. This makes the coolant jet turn faster which is then remained closer to the wall that results in higher film effectiveness. They also found that this effect is most influential at BR of close to 0.5 which is close to the presented test case. However, the effectiveness peak location for the current study was close to that of the literature and the detachment location and its length for the current study matched fairly well with that of the literature.

Figure 63 Round hole validation effort a) present study, b) from Baldauf et al. [9]

The determination of film effectiveness by OSP is compared with CO_2 concentration measured by gas sampling in Figure 65. The OSP results are extracted along the test section center line which passes through the center of one of the cooling holes as shown in Figure 64. It also passes through the centers of 10 gas sampling taps. Figure 65 shows the results for each test coupon at a blowing ratio of 1.0. The agreement in film cooling effectiveness is strong, providing confidence in the full-field film cooling results determined by OSP.

Figure 64 schematic of extracted OSP profile that is used for OSP vs gas sampling validation

**Figure 65 Comparisons of OSP vs gas sampling at
BR = 1.0 for the middle effectiveness profiles**

Each geometry was tested for all BR's within the same experimental run. This ensures that there is no temperature variation between various BR measurements and that the OSP CO₂-off to CO₂-on image intensity ratio versus CO₂ volume concentration would not change due to temperature differences between each set point. The gas sampling measurements agree well with the OSP results. The gas analysis has an asymptotic trend to a film cooling effectiveness of zero and that trend is also followed by the OSP profile. This asymptotic behavior has been shown by many sources in the literature [1, 35, 62, 14, 2].

3.2 DISCHARGE COEFFICIENTS

Discharge coefficients for all test coupons were calculated using the methodology provided by Gritsch et al. used for laid back fan shaped holes [46]. Mainly the discharge coefficients were found to be between 0.6 and 0.8. All coupons show an increase of discharge

coefficient with the increase of coolant plenum pressure ratio. The aluminum CNC coupon shows the highest discharge coefficient, as expected, followed by SLA and FDM 200 (Figure 66). The PolyJet discharge coefficient is lower than that of the FDM coupons which can be explained from the occurrence of jet separation (Figure 71, Figure 72 and Figure 73) as described by Gritsch [46] for the laidback fan shaped film holes. The separated coolant flow entering the diffuser section causes pressure recovery reduction and ultimately the reduction in discharge coefficient. The PolyJet low discharge coefficient also indicates that the coolant flow through the PolyJet coupon experiences more losses than the FDM 200, SLA and CNC aluminum coupons. SLA shows the same jet separation behavior; its in-hole roughness is likely to be much lower than that of the PolyJet. This may explain why its discharge coefficient outperforms the PolyJet coupon. Further investigation is required to confirm this supposition. It is unclear at this point why the diffuser flow separation occurs even though the in-hole roughness is most likely higher than that of SLA as evidenced by the discharge coefficient. For the FDM coupons, as build layer thickness increases, measured roughness on the outside of the film holes increases. The increase in roughness for the FDM coupons clearly resulted in lower discharge coefficients across the board.

Figure 66 Discharge coefficients for each test coupon for all BR's and coolant plenum pressure ratios, geometries sorted with the highest roughness first and decreasing on the left figure.

3.3 FILM EFFECTIVENESS RESULTS

3.3.1 LITERATURE COMPARISON

Film effectiveness results from the current study were compared to the literature. These comparisons are carried out by plotting centerline effectiveness (η_{CL}) vs Y/D , span averaged effectiveness ($\bar{\eta}$) vs Y/D and area averaged effectiveness ($\bar{\bar{\eta}}$) vs BR .

Figure 67 Centerline effectiveness plots comparing the CNC aluminum coupon to results from [2].

The plots presented in Figure 67 compare the centerline effectiveness of the CNC aluminum coupon to the results presented by Schroeder et al. [2]. The density ratios and BR 's are the same for both cases ($DR = 1.5$, $BR = 1.0 - 3.0$). However, the experimental technique and mainstream flow conditions are different. The present study employs mass transfer technique using OSP visualization technique with mainstream Mach number of 0.3 while [2] uses infra-red

thermography employing mainstream flow at ambient temperature and chilled coolant flow with approach Mach number of 0.03. This causes large difference in momentum flux ratio (I) and approach boundary layer thickness. The approach boundary layer thickness for the present study is $1.29D$ and the approach boundary layer for the Schroeder et al. [2] is $0.18D$. As expected, the results from the present study show lower effectiveness values due to thicker approach boundary layer. Even though the momentum flux ratio is lower for the present study, due to the thinner boundary layer thickness for the Schroeder et al. [2] case, the jet encounters a greater force from the mainstream that pushes it against the measurement plate as described by Eriksen et al. [61] which causes higher effectiveness for the Schroeder et al. [2] study. This is the main factor in lower centerline effectiveness measurement in the present study.

Figure 68 Area-averaged effectiveness comparison [2, 35] plotted as a function of the blowing ratio. Averaged over $Y/D = 2-22$ (right), geometry tested by Saumweber et al. [35] (left)

Area averaging in Figure 68 was done over the range of $Y/D = 2-22$ to compare the results from the present study to Saumweber et al. [35] and Schroeder et al. [2]. The results from Saumweber et al. [35] show much higher area averaged effectiveness. This is most likely because of higher DR and larger expansion angle that results in better film coverage. The area

averaged effectiveness is lower for the current study at BR of 1.0 and 1.5 and it becomes higher at BR of 2.0 and 2.5. There is a match of area averaged effectiveness at BR of 3.0. It appears that the area averaged effectiveness for the current study has the same shape but is shifted to the right by BR of 0.5. This is shown in Figure 69 left.

**Figure 69 Area averaged effectiveness comparison vs shifted BR values (left)
Area averaged effectiveness comparison with momentum flux ratio (right)**

The general shape of the area averaged effectiveness seems to collapse with the shifting of BR by 0.5. The reason behind the shift can be due to the vastly different mainstream Mach numbers and approach boundary layer thicknesses. Also, higher momentum flux ratio causes lower area averaged effectiveness at a given BR. This is because the mainstream pushes the coolant flow more severely to the measurement plate at lower momentum flux ratio and thinner approach boundary layer thickness. The comparison based on momentum flux ratio further confirms this observation (Figure 69 right).

Figure 70 Span averaged effectiveness plots comparing the CNC aluminum coupon to results from [2].

The results from the present study show higher effectiveness values near the film cooling holes and lower effectiveness far away from the film cooling holes. The approach boundary layer in the present study is a turbulent boundary layer with a viscous sublayer. This viscous sublayer is most likely the cause of higher effectiveness near the film holes. The higher viscosity in the viscous sublayer undermines mixing of the coolant flow and mainstream flow near the film holes. Far away from the film holes, even though the momentum flux ratio is lower for the present study, due to the thinner boundary layer thickness for the Schroeder et al. [2] case, the jet encounters a greater force from the mainstream that pushes it against the measurement plate as described by Eriksen et al. [61] which causes higher effectiveness for the Schroeder et al. [2].

3.3.2 FULL-FIELD FILM EFFECTIVENESS

The film effectiveness contour plots at $BR = 1.0$ and 1.5 for all test coupons are shown in Figure 71. The coupon with the lowest roughness value (SLA coupon, $Ra/D = 0.00545$) appears to show the earliest signs of diffuser flow separation ($-3 < Y/D_{SLA} < 0$) as evidenced by the visible asymmetry in the effectiveness contour starting within the exit ramp (fan region) of the film holes. On almost all of the film holes for this coupon the effectiveness is much higher on the film hole diffuser left sidewall than on the right.

Figure 71 Effectiveness contour comparison of various test coupons at $BR = 1.0$, $I = 0.58$ (left) $BR = 1.5$, $I = 1.18$ (right)

The PolyJet coupon ($Ra/D = 0.00905$) shows behavior most like the aluminum CNC case ($Re/D = 0.00650$) in the diffuser region ($-3 < Y/D < 0$). The SLA ($Ra/D = 0.00545$) and PolyJet coupons shown in Figure 72 with BR of 2.0 show early signs of increased asymmetry ($-3 < Y/D < 0$) while the rest of the test coupons appear to be in fully diffused regimes. At this BR the SLA is behaving different in a significant way than CNC aluminum. As the BR is increased all the way to 3.5 shown in Figure 73, all AM geometries show flow field deviations from the CNC

aluminum where all FDM coupons ($Ra/D = 0.00896-0.01288$) show fully diffused performance ($-3 < Y/D < 0$). Persh et al. [51] showed that a diffuser with a rougher throat internal surface had a delayed diffuser separation since the throat boundary layer was thickened and influenced the effective flow area. As a result, the effective diffuser divergence angle was decreased. This delays the occurrence of diffuser separation. In the present study, the same mechanism is the primary reason behind the delayed diffuser separation. The separated diffuser flow for the PolyJet coupon is most likely due to its in-hole roughness being higher than that of the SLA coupon and its discharge coefficient is lower also (Figure 71).

Figure 72 Effectiveness contour comparison of various test coupons at BR = 2.0, I = 1.85 (left) BR = 2.5, I = 2.52 (right)

The aluminum CNC coupon shows jet separation at its diffuser ($-3 < Y/D < 0$) which was different than the SLA and PolyJet coupons. During separated diffuser flow, the PolyJet and SLA coupons tend to exhibit flow separation laterally in the diffuser section which is different behavior from the aluminum CNC coupon. At BR of 3.5, (Figure 73) coolant flow separation is occurring by sidewall detachment for the SLA and PolyJet coupons. The aluminum CNC coupon

has reduced in-hole film effectiveness values ($\eta = 0.85-0.91$, $-3 < Y/D < 0$) that is dispersed across the laidback portion of its hole.

Figure 73 Effectiveness contour comparison of various test coupons at BR = 3.0, I = 3.16 (left) BR = 3.5, I = 3.76 (right)

3.3.3 SPAN AVERAGED EFFECTIVENESS

The Film cooling effectiveness is averaged in the span-wise direction over the middle three film holes and plotted in Figure 74. The film lift-off BR for the aluminum CNC coupon occurs at BR = 2.5 consistent with Schroeder et al. [2]. The film lift-off for SLA and PolyJet coupons is shifted to a lower BR of 2.0. The FDM coupons show much lower effectiveness values that tend to increase as the BR is increased (Figure 75). This is consistent with the findings of Bogard et al. [47] and Rutledge et al. [48]. Roughness causes turbulent mixing and diffusion to occur at the boundary layer. At higher BR's these changes prevent the jet from penetrating into the mainstream causing the effectiveness to increase. At lower BR's these changes cause the lift off BR to shift to a lower value. It is obvious that the change in manufacturing techniques has caused major differences in film effectiveness performance.

Figure 74 Span averaged film cooling effectiveness for each test coupon at various BR's

Figure 75 shows span averaged film effectiveness for all geometries for each BR. At BR of 1.0 and 1.5 the SLA coupon has the closest performance to the CNC aluminum. At BR of 2.0 the AM coupons show the highest divergent from the CNC aluminum. This is due to the shift in film lift off BR for the SLA and PolyJet coupons. The span averaged film effectiveness for the SLA and PolyJet coupons at BR of 2.0 have decreased from their highest peak which occurred at BR of 1.5 while the CNC aluminum coupon is at its highest peak. This is another way of describing the major changes in span averaged film effectiveness due to the change in manufacturing.

Figure 75 Span average effectiveness comparison for each BR across various test coupons

One way to examine the manufacturing accuracy of the test coupons is to assess the film effectiveness consistency between film cooling holes. This can be qualitatively studied by examination of the span averaged effectiveness for each hole excluding the holes near the wind tunnel side walls. In Figure 76 the film effectiveness is integrated separately for each hole, excluding the outermost ones at $BR = 2.5$. The PolyJet test coupon seems to have the best film cooling hole consistency followed by the aluminum CNC coupon. Perhaps due to geometrical repeatability issues, the FDM coupons exhibit large film effectiveness inconsistency. SLA coupon has inconsistent performance also most likely because the diffuser portions of the SLA film cooling holes are operating in a dissimilar fashion when in separated flow regime. This can also be seen in Figure 73 ($-3 < Y/D_{SLA} < 0$). The PolyJet however shows consistent hole by hole film effectiveness. There are two possible factors that account for this: first is the fact that PolyJet AM technique is known for its dimensional accuracy and repeatability [63] second is that

the film hole interior is probably the roughest that would cause a more consistent hole to hole diffuser performance as described by Persh et al. [51].

Figure 76 Individual hole span averages for film effectiveness consistency assessment at BR = 2.5, outermost holes are omitted

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

A new facility was constructed to conduct film-cooling experimentation at density ratio of 1.5 using mass transfer analogy. The facility employs both gas sampling and Oxygen Sensitive Paint (OSP) measurement techniques with good agreement between the two.

Multiple test coupons of 7-7-7 film hole geometry were manufactured using multiple 3D printing techniques with varying build layer thicknesses as well as a base line aluminum CNC coupon as a method to vary surface roughness inside and outside of the film cooling holes.

Surface roughness was measured for each test coupon and a trend for the inside roughness was estimated. The surface roughness increased significantly with the OSP application on the aluminum CNC test coupon.

The variation in 3D printing techniques and build layer thickness caused major differences both in qualitative and quantitative film adiabatic effectiveness measurements. This argues that great care should be exercised in performing film cooling experiments with additively manufactured film holes.

The adiabatic film cooling effectiveness measurements indicated that in-hole coolant separation was delayed for rougher parts with SLA and PolyJet parts presenting different in-hole coolant separation behavior than aluminum CNC. The FDM test coupons had the highest roughness values compared to that of SLA and they illustrated the most delay in Blowing Ratio (BR) of in-hole coolant separation. This is most likely due to boundary layer thickening of the inside wall of the film cooling hole by the roughness of the diffuser throat. This finding is consistent with the findings by Perch et al. [51]. The exception to this finding is the PolyJet

coupon with early diffuser flow separation and one of the lowest discharge coefficient values indicating its in-hole roughness to be much higher than that of SLA.

Discharge coefficients showed a clear trend for the FDM, SLA and aluminum CNC coupons where the rougher the coupon, the lower the discharge coefficient.

Rougher test coupons showed higher span averaged film cooling effectiveness at BR of 3.5 likely due to the film diffusion on the rough surface that prevents it from penetrating into the mainstream. This is a similar finding to Goldstein et al. [49]. The rougher test coupons showed lower effectiveness values at lower BR's due to increased turbulent mixing at the boundary layer.

The PolyJet coupon had the best consistency among film holes due to its dimensional accuracy and repeatability and in-hole roughness followed by the aluminum CNC coupon. FDM coupons did not show a consistent hole by hole performance due to dimensional repeatability issues. SLA coupon had variable hole by hole diffuser performance at separated flow regime causing inconsistent film effectiveness per film cooling hole.

None of the test coupons investigated showed consistent resemblance to the baseline test coupon (aluminum CNC). Although The SLA coupon had the closest roughness to the baseline test coupon, it showed dissimilar overall film effectiveness performance. This was the case with all of the test coupons. Therefore, at this scale the roughness produced by additive manufacturing is not comparable to the less rough, standard CNC machined parts.

To continue to investigate this phenomenon experimentally, one course of action is to verify film hole outlet velocity profiles either using hotwire anemometry or Particle Image Velocimetry (PIV). This can also be accomplished by manufacturing an oversized hole for better

special resolution. The effect of Ra/D can also be investigated this way. Metal powder AM is an interesting plan of investigation. The effect of build orientation is still unknown and an investigation is required to shed light on it. It is important to also investigate methodology to be able to scan and plot the internal features of each film hole and assess whether the conclusions made with the available measurement devices are valid.

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APPENDIX A1: OSP PROCESING MATLAB CODE

Contents

- reading input files
- Test Variables
- inputting constants
- calculating pixel scaling factor, we are converting pixels to inches here
- creating XY coordinates
- calculating Pressure Field manually
- Calibration coefficients are stored here
- calculating eta here we are calculating film cooling effectiveness (eta_OMS) from ISSI pressure field (P_OMS) and plotting it
- calculating Vol. % CO2
- calculating % difference between P_UC and P_OMS
- creating Binary File Outputs using mat2tecplot function

```
% Created by Paul Aghasi
% Last Modified by Paul Aghasi 02-19-2016

clear all;
clc;
close all;
```

Reading input files

Holes to be included in span average

```
Span_avg_holes = [0 0 1 1 1 0 0];

% Geometry = 'Geom 3';
% Geometry = 'Geom 4-2';
% Geometry = 'PSU 7-7-7';
% Geometry = 'Sweeping_Jet';
Geometry = 'Poly Jet 1';
IGTI = '1';
% date = '06-08-2015';
% Mach = ' 0_16';
Mach = ' 0_3';
Taps = ' 10';
% BR = ' 0_6';
% Taps = ' No';
% BR = ' 0_5';
BR = ' 1_0';
% BR = ' 1_5';
% BR = ' 2_0';
% BR = ' 2_5';
% BR = ' 3_0';
% BR = ' 3_5';
% BR = ' 4_0';
```



```

% BR = ' 4_5';
% date = '05-28-2015';
date = '10-01-2015';
notes = ''; % notes are placed after BR
Date_list1 = {'08-04-2015'
'08-05-2015'
'08-06-2015'
'08-07-2015'
'08-10-2015'
'08-12-2015'
'08-13-2015'
'08-14-2015'
'08-17-2015'
'08-18-2015'
'08-20-2015'
'08-21-2015'
'08-27-2015'};

Date_list2 = {'08-28-2015'
'08-31-2015'};

Date_list3 = {'10-01-2015'};

Date_list4 = {'10-02-2015'};

Date_list5 = {'10-04-2015'
'10-07-2015'};

Date_list6 = {'10-08-2015'};

Date_list7 = {'10-30-2015'
'10-31-2015'
'11-01-2015'};

if strcmp(Geometry, 'Geom', 4) == 1
ReadDirectory = strcat('\Psp-computer\g\Data Files\',Geometry,'\ ',date,' BR ',BR,' M
',Mach,'\Averaged'); %change this to where you have all of your image files
elseif strcmp(Geometry, 'PSU', 3) == 1 || strcmp(Geometry, 'Sweeping_Jet',12) == 1
|| strcmp(IGTI, '1',1) == 1
ReadDirectory = strcat('\PSP-COMPUTER\Users\Turbine Film Cooling\Desktop\Data
Files\',Geometry,'\ ',date,' BR ',BR,' M ',Mach,'\Averaged');
end
OutputDirectory = 'C:\Users\Paul\Desktop\Film Cooling Processed Data\Tecplot
Files\Data Files\PSP';
OutputDirectory_Profile = 'C:\Users\Paul\Desktop\Film Cooling Processed Data\Tecplot
Files\Data Files\PSP\Profiles';
filename = strcat(ReadDirectory,'\ ',date,' BR ',BR,' M ',Mach, 'Taps, '
Taps_Pressure','.b16'); %this is the pressure field file output by ISSI
software used for comparison
filename_mean_eta = strcat(OutputDirectory_Profile,'\ ',Geometry,' BR ',BR, notes,' M
',Mach,' Span eta.dat');

```

```
filename_mean_eta_holes = strcat(OutputDirectory_Profile,'\ ',Geometry,' BR ',BR,
notes,' M ',Mach,' Span eta all holes.dat');
filename3 = strcat(OutputDirectory,'\ ',Geometry,' BR ',BR, notes,' M ',Mach,'.plt');
```

Test Variables

```
Pbaro = 14.411968414576121;

T_test = round(18.762968587217308); % test section temperature (deg C)
P_test = 1.014776200891703e+05; % test section pressure (Pa)
X_CO2c = 91.311647635964249; % molar fraction of CO2 in coolant we use this for our
film cooling effectiveness calculation
X_CO2c = X_CO2c/100;

% here the file name convention is as follows:
% WD = Wind
% DRK = Dark
% BRT = Bright (with illumination turned on)
% REF = Reference
% SIG = Signal
% so WD_OFF_DRK_REF indicates 'wind off dark reference'
filename_WDoffDRK_ref = strcat(ReadDirectory,'\ ', 'WD_OFF_DRK_REF', '.b16');
filename_WDonDRK_ref = strcat(ReadDirectory,'\ ', 'WD_ON_DRK_REF', '.b16');
filename_WDoffBRT_ref = strcat(ReadDirectory,'\ ', 'WD_OFF_BRT_REF', '.b16');
filename_WDonBRT_ref = strcat(ReadDirectory,'\ ', 'WD_ON_BRT_REF', '.b16');
filename_WDoffDRK_sig = strcat(ReadDirectory,'\ ', 'WD_OFF_DRK_SIG', '.b16');
filename_WDonDRK_sig = strcat(ReadDirectory,'\ ', 'WD_ON_DRK_SIG', '.b16');
filename_WDoffBRT_sig = strcat(ReadDirectory,'\ ', 'WD_OFF_BRT_SIG', '.b16');
filename_WDonBRT_sig = strcat(ReadDirectory,'\ ', 'WD_ON_BRT_SIG', '.b16');

% ReadOMS_b16 will convert the .b16 file (binary file) into 3 matrices,
% first one is rows (in this case 800 X 1 in size)
% second one is columns
% third one is a matrix of intensity values per pixel in a size of rows X
% columns
% the input to this function is the filepath
[row,col,P_OMS] = readOMS_b16(filename);

[row,col,WDoffDRK_ref] = readOMS_b16(filename_WDoffDRK_ref);
[row,col,WDonDRK_ref] = readOMS_b16(filename_WDonDRK_ref);
[row,col,WDoffBRT_ref] = readOMS_b16(filename_WDoffBRT_ref);
[row,col,WDonBRT_ref] = readOMS_b16(filename_WDonBRT_ref);
[row,col,WDoffDRK_sig] = readOMS_b16(filename_WDoffDRK_sig);
[row,col,WDonDRK_sig] = readOMS_b16(filename_WDonDRK_sig);
[row,col,WDoffBRT_sig] = readOMS_b16(filename_WDoffBRT_sig);
[row,col,WDonBRT_sig] = readOMS_b16(filename_WDonBRT_sig);

% the markers are used to compare our gas analysis results to our PSP
% results

if strcmp(date,'06-23-2015') == 1
```

```

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate)
MX = [509.868    478.745    447.717    416.51    509.718    478.586    446.988
415.73];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate)
MY = [151.616    150.755    150.76    150.701    404.684    404.856    404.643
404.699];

% Ports to average:
MX2 = [446.508    447.877    447.903    447.809    447.826    447.796    447.882
447.861    447.743    447.769];
MY2 = [70.8704    150.595    182.552    213.758    245.613    277.614    309.573
341.438    373.382    404.634];

elseif any(strcmp(date,Date_list1) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MX = [541.939    507.996    473.996    439.94    541.963    507.978    472.86
438.98];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MY = [172.971    172.986    172.921    171.913    449.93    449.952    449.925
448.977];

% Ports to average:
MX2 = [471.971    473.997    473.937    473.977    473.951    473.931    473.996
473.922    473.986    472.868];
MY2 = [84.9014    172.925    206.953    241.947    275.906    310.887    345.962
379.85    414.956    449.93];

elseif any(strcmp(date,Date_list3) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MX = [472.785    437.509    401.568    365.759    472.427    436.773    400.89
365.583];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MY = [166.627    165.991    165.958    165.738    455.636    455.413    454.603
454.977];

% Ports to average:
MX2 = [400.617    401.566    401.807    401.8    401.598    401.568    401.507
400.859    400.968    400.884];
MY2 = [74.812    165.96    202.607    238.674    274.951    310.992    346.944
382.618    419.5    454.604];

```

```

elseif any(strcmp(date,Date_list4) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MX = [540.988    505    468.979    433.963    540.949    504.946    468.973
432.977];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MY = [165.951    165.936    165.901    164.995    455.994    455.998    455.992
454.997];

% Ports to average:
MX2 = [467.992    468.98    468.99    468.994    468.996    468.999    468.98
468.912    468.976    468.975];
MY2 = [73.9575    165.906    201.964    238.934    274.958    310.948    346.964
383.953    419.983    455.992];

elseif any(strcmp(date,Date_list5) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MX = [473.926    437.951    401.947    365.958    473.993    437.914    401.999
365.973];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MY = [167.974    167.984    167.988    167.985    458.992    459.954    458.975
458.971];

% Ports to average:
MX2 = [399.996    401.95    401.968    401.974    401.962    401.977    401.973
401.943    401.968    401.999];
MY2 = [76.9198    167.989    204.999    240.982    276.981    313.999    350.938
386.971    422.95    458.977];

elseif any(strcmp(date,Date_list6) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MX = [472.998    436.999    400.978    364.994    473.966    436.998    401.922
364.996];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate flowed by second row from right to left)
MY = [166.958    166.968    166.942    166.976    458.958    458.923    457.985
458.959];

% Ports to average:
MX2 = [399.976    400.979    400.992    400.992    400.993    401.972    401.971
401.924    401.983    401.926];
MY2 = [74.8315    166.945    203.898    239.95    276.959    312.964    349.929
385.916    421.988    457.986];

```

```

elseif any(strcmp(date,Date_list7) == 1)

% Markers X Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MX = [436.994    400.985    364.989    328.969    437.979    401.958    365.986
329.977];
% Markers Y Coordinates in pixels obtained from ISSI software (1st row on
% the aluminum plate followed by second row from right to left)
MY = [161.985    161.962    162.915    162.938    452.983    452.989    452.953
452.96];

% Ports to average:
MX2 = [363.989    364.99    364.993    364.99    364.983    364.995    365.974
365.973    365.998    365.987];
MY2 = [70.9536    162.919    198.945    234.993    271.923    307.972    343.98
380.94    416.98    452.956];

else

% Markers X Coordinates in pixels obtained from ISSI software
MX = [501.831    470.992    439.863    408.966    501.89    470.943    439.874
407.844];
% Markers Y Coordinates in pixels obtained from ISSI software
MY = [149.908    149.94    148.898    148.865    402.93    402.929    402.793
402.918];

% Ports to average:
MX2 = [437.945    439.863    439.95    439.994    439.909    439.892    439.946
439.957    439.89    439.874];
MY2 = [68.9642    148.898    180.928    212.85    243.908    275.891    307.897
338.926    370.808    402.793];

end

```

Inputting constants

```

To_psi = 0.000145037738; % this will convert Pa to psi

MX = round(MX) + 1; % here we are offsetting the pixel coordinate for the center of
averaging domain (circular in shape)
MY = round(MY) + 1;
MX2 = round(MX2) + 2; % here we are offsetting the pixel coordinate for the center of
averaging domain (circular in shape)
MY2 = round(MY2) + 2;
D_avg = 8;          % Diameter to average in pixels
R_avg = D_avg/2;    % radius to average in pixels
Vertical_Distance = 4; % vertical distance of the first row of taps on aluminum plate
from the last row of taps on the aluminum plate

if strcmp(Geometry, '30 Deg round', 12) == 1

```

```

Diameter = 0.1; %hole Diameter (inches)
% Height = 1.65; % First Row distance to the Film hole Center (inches)
Height = 2.00; % First Row distance to the Film hole Center (inches)
Pitch = 6; % Pitch Spacing of the holes in units of hole diameter, used in span
averaging

else

Diameter = 0.1; % Film hole Diameter (inches)
Height = 1.8; % First Row distance to the Film hole Center (inches)
Pitch = 6; % Pitch Spacing of the holes in units of hole diameter, used in span
averaging

end

X_O2air = 0.209476; % assumed molar fraction of oxygen in air
W_CO2 = 44.0095; % molecular weight of CO2
W_air = 28.9652; % molecular weight of air
W_O2 = 15.9994; % molecular weight of O2
DR = W_CO2/W_air;
hole_numb = size(Span_avg_holes,2);

% paint calibration constants, refer to the provided documentation for the
% meaning behind each constant, this was provided by ISSI and will vary
% based on paint type
% refer to line 158 to see the implementation of these coefficients
A = -29111.32;
B = 114117;
C = 16891.2;
D = 386.101;
E = -140.924;
F = -349.867;
H = -6.45057;
J = 0.652218;
K = 0.304657;

```

Calculating pixel scaling factor, we are converting pixels to inches here

```

dist1 = sqrt((MX(3)-MX(7))^2 + (MY(3)-MY(7))^2);
Pixel_Scaling_Factor = (Vertical_Distance / Diameter)/dist1;

```

Creating XY coordinates

```

rwclX = zeros(size(P_OMS));
rwclY = zeros(size(P_OMS));

for j = 1:size(P_OMS,2)

for i = 1:size(P_OMS,1)

    rwclX(i,j) = j;
    rwclY(i,j) = i;

```

```
end
```

```
end
```

```
rwclX = (rwclX-MX(3)) * Pixel_Scaling_Factor;  
rwclY = rwclY * Pixel_Scaling_Factor - (MY(3) * Pixel_Scaling_Factor-  
(Height/Diameter));
```

Calculating Pressure Field manually

Subtracting the dark image to compensate for any possible ambient light:

```
WDoFF_ref = WDoFFBRT_ref - WDoFFDRK_ref;
```

```
WDon_ref = WDonBRT_ref - WDonDRK_ref;
```

```
WDoFF_sig = WDoFFBRT_sig - WDoFFDRK_sig;
```

```
WDon_sig = WDonBRT_sig - WDonDRK_sig;
```

```
% deviding wind off by wind on images (int_ratio refers to intensity ratio):
```

```
int_ratio_ref = WDoFF_ref ./ WDon_ref;
```

```
int_ratio_sig = WDoFF_sig ./ WDon_sig;
```

```
% deviding signal intensity ratio by reference intensity ratio
```

```
int_UC = int_ratio_sig ./int_ratio_ref;
```

```
P_UC = A + B*int_UC + C*int_UC.^2 + T_test * (D + E*int_UC + F*int_UC.^2) + T_test^2 *  
(H + J*int_UC + K*int_UC.^2);
```

```
P_UC = (P_UC ./ 100000 * P_test)*To_psi;
```

Calibration coefficients are stored here

```
if strcmp(Geometry, 'Poly Jet 1') == 1 && strcmp(date, '10-01-2015') == 1 % &&  
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1
```

```
% Poly Jet 1 Coefficients 10-01-2015 BR 1.0
```

```
% actual coefficients
```

```
coeff =1.0e5 * [9.65707876176933770000
```

```
1.09620070730620120000
```

```
4.68788089662689430000
```

```
-0.40267257793145456000
```

```
0.32884568008691983000
```

```
0.04110307376136120700
```

```
-0.00400904190657349560
```

```
-0.01918279054486652200
```

```
-0.01377487768647050300];
```

```

elseif strcmp(Geometry, 'Poly Jet 2') == 1 && strcmp(date, '10-02-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Poly Jet 2 Coefficients 10-02-2015 BR 1.0
coeff =1.0e5 * [9.65707876176902500000
1.09620070731079400000
4.68788089662247120000
-0.40267257794093103000
0.32884568017879834000
0.04110307367120439500
-0.00400904209604925190
-0.01918278870730888100
-0.01377487948960634000];

elseif strcmp(Geometry, 'Poly Jet 3') == 1 && strcmp(date, '10-04-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Poly Jet 3 Coefficients 10-04-2015 BR 1.0
coeff =1.0e5 * [9.65707876176866980000
1.09620070731084310000
4.68788089662182910000
-0.40267257794352479000
0.32884568017979482000
0.04110307366137828200
-0.00400904214793233560
-0.01918278868735701400
-0.01377487968612883100];

elseif strcmp(Geometry, 'MB 200') == 1 && strcmp(date, '10-04-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Maker Bot 200 Micron Coefficients 10-04-2015 BR 1.0
coeff =1.0e5 * [9.65707876176536930000
1.09620070734073870000
4.68788089659460370000
-0.40267257801281192000
0.32884568077768211000
0.04110307311547318300
-0.00400904353370348970
-0.01918277672960378200
-0.01377489060423213300];

elseif strcmp(Geometry, 'MB 250') == 1 && strcmp(date, '10-07-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Maker Bot 250 Micron Coefficients 10-07-2015 BR 1.0
coeff =1.0e5 * [9.65707876176789170000
1.09620070732099610000
4.68788089661257510000
-0.40267257796021588000
0.32884568038284373000

```



```

0.04110307347498305000
-0.00400904248180501860
-0.01918278462638332500
-0.01377488341403877400];

elseif strcmp(Geometry, 'MB 300') == 1 && strcmp(date, '10-08-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Maker Bot 300 Micron Coefficients 10-08-2015 BR 1.0
coeff =1.0e5 * [9.65707876177151190000
1.09620070729634040000
4.68788089663601950000
-0.40267257788897132000
0.32884567988965724000
0.04110307394317509700
-0.00400904105691120460
-0.01918279449009696300
-0.01377487405019790100];

elseif strcmp(Geometry, 'Aluminum 7-7-7') == 1 && strcmp(date, '10-30-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% Aluminum 7-7-7 Coefficients 10-30-2015 BR 1.0
coeff =1.0e5 * [9.65707876176856320000
1.09620070731396320000
4.68788089661883500000
-0.40267257794809613000
0.32884568024229849000
0.04110307360014282800
-0.00400904223940367480
-0.01918278743728657800
-0.01377488091084310400];

elseif strcmp(Geometry, '30 Deg round') == 1 && strcmp(date, '10-31-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% 30 Deg round hole Coefficients 10-31-2015 BR 0.6
coeff =1.0e5 * [9.65707876176823280000
1.09620070731644190000
4.68788089661759510000
-0.40267257795314737000
0.32884568029176797000
0.04110307357550387800
-0.00400904234041534520
-0.01918278644787914700
-0.01377488140361833200];

elseif strcmp(Geometry, '30 Deg roundII') == 1 && strcmp(date, '11-01-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% 30 Deg round hole Coefficients 11-01-2015 BR 0.6
coeff =1.0e5 * [9.65707876176897880000

```

```

1.09620070730913800000
4.68788089662512240000
-0.40267257793932321000
0.32884568014558352000
0.04110307372514887500
-0.00400904206394786610
-0.01918278937159321700
-0.01377487841072243400];

elseif strcmp(Geometry, 'SLA PSU') == 1 && strcmp(date, '10-31-2015') == 1 % &&
strcmp(BR, '1_0') == 1 && strcmp(Mach, '0_3') == 1

% SLA PSU Coefficients 10-31-2015 BR 1.0
coeff = 1.0e5 * [9.65707876176716340000
1.09620070732545140000
4.68788089661009890000
-0.40267257797689748000
0.32884568047193385000
0.04110307342544133200
-0.00400904281540836670
-0.01918278284458125500
-0.01377488440487010700];

end

T_test2 = 20;

CO2_UC = coeff(1) + coeff(2)*int_UC + coeff(3)*int_UC.^2 + T_test2 * (coeff(4) +
coeff(5)*int_UC + coeff(6)*int_UC.^2) + T_test2^2 * (coeff(7) + coeff(8)*int_UC +
coeff(9)*int_UC.^2);

% CO2_UC = CO2_Curve_fit;

% the 100000 Pa value used in this line is the pressure at which ISSI has
% decided to normalize their calibration curve with
CO2plen = X_CO2c;
O2_Percent = (1-CO2_UC) .* X_O2air;
X_airwall = O2_Percent ./ X_O2air; % molar fraction of air at the wall
W_w = (1 - X_airwall) .* W_CO2 + X_airwall .* W_air; % molecular weight of the mixture
at the wall
X_O2c = X_O2air * (1-CO2plen); % molar fraction of O2 at coolant plenum
X_airc = CO2plen / X_O2air; % molar fraction of air at coolant plenum
W_c = (CO2plen * W_CO2) + (X_airc * W_air); % molecular weight of the coolant gas
mixture
C_O2wall = O2_Percent .* W_O2 ./ W_w; %mass fraction of CO2 at wall
C_O2air = X_O2air * W_O2 / W_air; %mass fraction of CO2 at air plenum
C_O2coolant = X_O2c * W_O2 / W_c; %mass fraction of CO2 at coolant plenum
eta_Cal = 1-1 ./ (1 + (X_O2air ./ O2_Percent - 1) .* (W_w ./ W_air)); %eta

```

Calculating eta here we are calculating film cooling effectiveness (eta_OMS) from ISSI pressure field (P_OMS) and plotting it

```

eta_OMS = zeros(size(P_UC));

X_O2wall_OMS = (P_UC / Pbaro) * X_O2air; % O2 molar fraction at the wall
X_airwall_OMS = X_O2wall_OMS / X_O2air; % molar fraction of air at the wall
W_w_OMS = (1 - X_airwall_OMS) * W_CO2 + X_airwall_OMS * W_air; % molecular weight of
the mixture at the wall
X_O2c_OMS = X_O2air * (1-X_CO2c); % molar fraction of O2 at coolant plenum
X_airc_OMS = X_O2c_OMS / X_O2air; % molar fraction of air at coolant plenum
W_c_OMS = (X_CO2c * W_CO2) + (X_airc_OMS * W_air); % molecular weight of the coolant
gas mixture
C_O2wall_OMS = X_O2wall_OMS * W_O2 ./ W_w_OMS; %mass fraction of CO2 at wall
C_O2air_OMS = X_O2air * W_O2 / W_air; %mass fraction of CO2 at air plenum
C_O2coolant_OMS = X_O2c_OMS * W_O2 / W_c_OMS; %mass fraction of CO2 at coolant plenum
eta_OMS = 1-1 ./ (1 + (X_O2air ./ X_O2wall_OMS - 1) .* (W_w_OMS ./ W_air)); %eta

```

Calculating Vol. % CO2

```

Per_CO2 = (-P_UC*To_psi+Pbaro)/Pbaro * 100;

```

Calculating % difference between P_UC and P_OMS

```

diff = zeros(size(P_OMS));
for j=1:size(P_OMS,2)

    for i = 1:size(P_OMS,1)

        if P_OMS(i,j) ~= 0 && eta_Cal(i,j) > 0

            diff(i,j) = ((P_OMS(i,j)*To_psi) - P_UC(i,j))./(P_OMS(i,j)*To_psi) * 100;

        elseif eta_Cal(i,j) < 0;

            eta_OMS(i,j) = 0.000;
            eta_Cal(i,j) = 0.000;
            CO2_UC(i,j) = 0.000;

        else

            eta_OMS(i,j) = 0;
            eta_Cal(i,j) = 0;
            int_UC(i,j) = 0;
            CO2_UC(i,j) = 0;

        end
    end
end

cmap = colormap(jet(101));
cmap(1,3) = 0;
cmap(size(cmap,1),1) = 0;
colormap(cmap);
imagesc(eta_Cal,[0,1])
set(gca,'YDir','normal');

```

```

colorbar

ang=0:0.01:2*pi;
yp=R_avg*sin(ang);
xp=R_avg*cos(ang);
for k = 1:size(MX2,2)
l = 0;
clearvars M_Avg M_Avg_int
hold on
plot(MX2(k)+xp,MY2(k)+yp,'r','LineWidth',1);
for j = 1:row
for i = 1:col
    dist(i,j) = (i - MX2(k))^2 + (j - MY2(k))^2;
    if dist(i,j)<= R_avg^2 && P_OMS(j,i)~=0
        l = l+1;
        M_Avg(l,1) = eta_Cal(j,i);
        M_Avg_int(l,1) = int_UC(j,i);
        M_Avg(l,2) = j;
        M_Avg(l,3) = i;
    end
end

end
end
M_Avg(M_Avg == 0) = [];
M_Avg_int(M_Avg_int == 0) = [];
M_PSP(k) = mean(M_Avg(:,1));
M_int(k) = mean(M_Avg_int);

end
CELLS = num2cell(M_PSP');
clipboard('copy',sprintf('%s\n', CELLS{:}))
M_int'
eta_max = max(eta_Cal(:));
CELLS = num2cell(eta_max);

int_min = min(int_UC(int_UC>0))

% finding out the indexes for the border of each hole in x direction
% (spanwise)

for i = 1:hole_numb+1

    [hole_row(i),hole_col(i)] = find(rwclX>((-hole_numb*Pitch/2) + (i-1)*Pitch),1);
    hold on
    line([hole_col(i) hole_col(i)], [0 600], 'Color','w')

end

% storing the eta values for each respective hole into a cell array of
% eta_holes, each index contains

```

```

for i = 1:hole_numb

eta_holes{i} = eta_Cal(:,hole_col(i):hole_col(i+1));

end

% Span averaging each hole separately
for i = 1:hole_numb

mean_eta_holes{i}(:,1) = rwclY(:,1);
mean_eta_holes{i}(:,2) = sum(eta_holes{i},2)./sum(eta_holes{i}~=0,2);

end

% we are separating the Y/D coordinate and deleting the holes that we do
% not want
m = [mean_eta_holes{:}];
m(:,1:2:end) = []; % getting rid of the Y/D Columns
m(:,Span_avg_holes==0)=[]; % eliminating the holes to be excluded from averaging
meaneta_each_hole = [mean_eta_holes{:}];
meaneta_each_hole(:,1:2:end) = []; % getting rid of the Y/D Columns
meaneta_each_hole(:,1)=rwclY(:,1); % replacing 1st column with Y/D
meaneta_each_hole(:,7)=[]; % eliminating the side holes to be excluded from averaging

figure(1); hold on;

for i = 1:hole_numb

    if Span_avg_holes(i) == 1

        p = patch([hole_col(i) hole_col(i+1) hole_col(i+1) hole_col(i)], [1 1 row row],
'r');
        set(p,'FaceAlpha',0.4);

    end

end

meaneta(:,2) = sum(m,2)./sum(m~=0,2);
meaneta(:,1) = rwclY(:,1);
meaneta(isnan(meaneta)) = 0;
meaneta_each_hole(isnan(meaneta_each_hole)) = 0;

integrated_eta(:,1) = rwclY(:,1);
integrated_eta(:,2) = trapz(rwclX(1,:),eta_Cal,2);

BR = strrep(BR, '_', '.');
Mach = strrep(Mach, '_', '.');
fID = fopen(filename_mean_eta,'wt');
Header = {strcat('VARIABLES = "Y/D"',...
' "_\n<greek>h</greek>"',...

```

```

strcat('ZONE T=',Geometry,' BR ',BR,'');
fprintf(fID,'%s\n',Header{1},Header{2},Header{3});
fclose(fID);
dlmwrite(filename_mean_eta,meaneta,'-append','delimiter',' ','precision','%0.13f');

fID = fopen(filename_mean_eta_holes,'Wt');
Header = {strcat('VARIABLES = "Y/D"',...
' "hole 1" "hole 2" "hole 3" "hole 4" "hole 5" ',...
strcat('ZONE T=',Geometry,' BR ',BR,''))};
fprintf(fID,'%s\n',Header{:});
fclose(fID);
dlmwrite(filename_mean_eta_holes,meaneta_each_hole,'-append','delimiter','
','precision','%0.13f');

```

ans =

```

0.699902857047648
0.880462346906673
0.909698127654358
0.931271809346547
0.939247639616879
0.948931909896991
0.958841653034794
0.958455521082917
0.962906992380893
0.965722320261588

```

int_min =

```

0.139670859045498

```

Creating Binary File Outputs using `mat2tecplot` function

First we need to define the 'tdata' structure where it includes the variables names, zone names, orientation and finally the actual values in matrix form

```
Zone_Name = [Geometry, ' BR =', BR, ', M = ', Mach];
tdata=[];
tdata.varnames={ 'X/D'
                  'Y/D'
                  'z'
                  'P OMS (psia) '
                  '%CO2'
                  '<greek>h</greek>'
                  '<greek>h</greek><sub>Calibrated</sub>'
                  'I<sub>sig</sub>/I<sub>ref</sub>'
                  'I<sub>WD off DRK ref</sub>'
                  'I<sub>WD on DRK ref</sub>'
                  'I<sub>WD off BRT ref</sub>'
                  'I<sub>WD on BRT ref</sub>'
                  'I<sub>WD off DRK sig</sub>'
                  'I<sub>WD on DRK sig</sub>'
                  'I<sub>WD off BRT sig</sub>'
                  'I<sub>WD on BRT sig</sub>'
                  'I<sub>WD off ref</sub>'
                  'I<sub>WD on ref</sub>'
                  'I<sub>WD off sig</sub>'}
```



```

%                                     nodal.
%                                     if x not available, default
%                                     to zero

tdata.surfaces(1).v(1, :, :) = P_OMS.*To_psi;%---2D variables defined on the
%                                     surface (optional). Default to
%                                     zeros if Nvar>3

tdata.surfaces(1).v(2, :, :) = CO2_UC;
tdata.surfaces(1).v(3, :, :) = eta_OMS;
tdata.surfaces(1).v(4, :, :) = eta_Cal;
tdata.surfaces(1).v(5, :, :) = int_UC;
tdata.surfaces(1).v(6, :, :) = WDoFFDRK_ref;
tdata.surfaces(1).v(7, :, :) = WDonDRK_ref;
tdata.surfaces(1).v(8, :, :) = WDoFFBRT_ref;
tdata.surfaces(1).v(9, :, :) = WDonBRT_ref;
tdata.surfaces(1).v(10, :, :) = WDoFFDRK_sig;
tdata.surfaces(1).v(11, :, :) = WDonDRK_sig;
tdata.surfaces(1).v(12, :, :) = WDoFFBRT_sig;
tdata.surfaces(1).v(13, :, :) = WDonBRT_sig;
tdata.surfaces(1).v(14, :, :) = WDoFFBRT_ref - WDoFFDRK_ref;
tdata.surfaces(1).v(15, :, :) = WDonBRT_ref - WDonDRK_ref;
tdata.surfaces(1).v(16, :, :) = WDoFFBRT_sig - WDoFFDRK_sig;
tdata.surfaces(1).v(17, :, :) = WDonBRT_sig - WDonDRK_sig;
tdata.surfaces(1).v(18, :, :) = P_UC;
tdata.surfaces(1).v(19, :, :) = diff;

mat2tecplot(tdata,filename3)

BR = strrep(BR, '.', '_');
Mach = strrep(Mach, '.', '_');

```

ans =

1

ans =

0

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APPENDIX A2: LABVIEW DATA REDUCTION MATLAB CODE

Contents

- Reading input files and creating output file names, also generating MATLAB storage files if one doesn't already exist
- Assigning relevant names to each stored content from the TDMS file
- calculating CO2 mass flux, jet velocity, mainstream velocity, momentum flux ratio and discharge coefficient
- mapping out each sampling valve position
- assigning the sampling valve ports to their respective names
- calculating eta from gas analysis
- writing a file that contains eta from gas analysis along with the locations of ports as a multiple of film hole diameter
- calculating SCFM of coolant and flow coefficient (Cv)
- calculating discharge coefficient

```
clc

clear all
close all
% Geometry = 'PSU 7-7-7';
% Geometry = 'Geometry 4-2';
% Geometry = 'Geom 6';
Geometry = 'Poly Jet 1';
% Geometry = 'Sweeping_Jet';
% Mach = ' 0_16';
Mach = ' 0_3';
Taps = '10';
% Taps = 'No';

% BR = ' 0_85';
% BR = ' 0_5';
BR = ' 1_0';
% BR = ' 1_5';
% BR = ' 2_0';
% BR = ' 2_5';
% BR = ' 3_0';
% BR = ' 3_5';
% BR = ' 4_0';
% BR = ' 4_5';
date = '10-01-2015';
Averaged_Smaples = 10; % averaged last 10 second of recording per port
ReadDirectory = 'C:\Users\Paul\Desktop\Film Cooling Processed Data\TDMS Files';
name = [date, ' ', Geometry, ' PSP BR', BR, ' M', Mach, ' ', Taps, ' Taps'];
OutputDirectory_Profile = 'C:\Users\Paul\Desktop\Film Cooling Processed Data\Tecplot
Files\Data Files\PSP\Profiles';

if strcmp(Geometry, 'Geometry', 8) == 1

Geometry = strrep(Geometry, 'Geometry', 'Geom');
```

```
end
```

Reading input files and creating output file names, also generating MATLAB storage files if one doesn't already exist

```
filename_mean_eta = strcat(OutputDirectory_Profile, '\\', Geometry, ' Gas Analysis BR  
,BR, ' M ',Mach, '.dat');  
filename = strcat(ReadDirectory, '\\', name, '.mat');  
  
if exist(filename, 'file') == 2  
  
    load(filename);  
else  
    filename = strcat(ReadDirectory, '\\', name, '.tdms');  
    matFileName=simpleConvertTDMS(filename);  
    load(matFileName{1});  
  
end
```

Assigning relevant names to each stored content from the TDMS file

```
TimeLength =  
LowSpeedGas_AnalyzerMean.Property.wf_increment*LowSpeedGas_AnalyzerMean.Total_Samples;  
  
Time = linspace(0,TimeLength,LowSpeedTestSectionMach.Total_Samples);  
  
Gas_Analyzer = LowSpeedGas_AnalyzerMean.Data; % CO2 % data  
Mach = LowSpeedTestSectionMach.Data; % Mach number  
massflow = LowSpeedAirMassFlowRateIbs.Data; % air mass flow lbm/s  
massflowCO2 = LowSpeedCO2MassFlowRateIbs.Data;% coolant mass flow lbm/s  
BR_Matrix = LowSpeedBlowingRatio.Data; % BR  
SV1 = LowSpeedSamplingValve1.Data; % position of sampling valve 1  
SV2 = LowSpeedSamplingValve2.Data; % position of sampling valve 2  
SV3 = LowSpeedSamplingValve3.Data; % position of sampling valve 3  
Pbaro = LowSpeedBarometric_PMean.Data; % Barometric Pressure psia  
T_test = LowSpeedAirPlenum_TMean.Data; % airplenum temperature degF  
T_CO2 = LowSpeedCO2Line_TMean.Data; % coolant upstream sonic nozzle temperature degF  
P_test = LowSpeedAir_PlenumMean.Data; % air plenum pressure psig  
P_line = LowSpeedPre_Nozz_AirMean.Data; % mainstream upstream sonic nozzle temperature  
psig  
P_tank = LowSpeedTankPMean.Data; % supply pressure psig  
P_test = P_test + Pbaro; % air plenum pressure psia  
P_CO2 = LowSpeedCO2_PlenumMean.Data; % coolant plenum pressure psig  
Pressure_Ratio = (P_CO2 + Pbaro)./Pbaro; % coolant plenum pressure ratio  
Aco2 = pi*(0.1/2)^2*7/144; % coolant holes area ft2  
Aair = 6/144; % mainstream inlet area ft2  
m_CO2 = 44.01; % molecular weight of CO2  
g_CO2 = 1.28; % ratio of specific heats of CO2  
m_air = 28.9; % molecular weight of air  
Rco2 = 1545.348/m_CO2; % specific gas constant of CO2  
Rair = 1545.348/m_air; % specific gas constant of air
```

```
gc = 32.2; % gravitational acceleration
PR = mean(Pressure_Ratio); % mean coolant plenum pressure ratio
CO2_massFlow = (LowSpeedCO2MassFlowRateIbs.Data); % coolant mass flow lbm/s
```

Calculating CO2 mass flux, jet velocity, mainstream velocity, momentum flux ratio and discharge coefficient

```
CO2_massFlux = mean(LowSpeedCO2MassFlowRateIbs.Data) / (pi*(0.1/2)^2*7);
V_CO2 = massflowCO2./ (Aco2 .* ((P_CO2+Pbaro)*144) ./ (Rco2.*(T_CO2+460)));
V_air = massflow./ (Aair .* ((Pbaro).*144) ./ (Rair.*(T_test+460)));
I_Matrix = BR_Matrix .* (V_CO2./V_air);
FFT2 = sqrt((gc*g_CO2)/Rco2) * sqrt((2/(g_CO2-1))*PR^(-
((g_CO2+1)/g_CO2))*(PR^(((g_CO2-1)/g_CO2))-1));
Ae = (mean(massflowCO2)*sqrt(mean(T_CO2)+459.67))/(((mean(P_CO2) +
mean(Pbaro))*144)*FFT2);
Cd = Ae/Aco2;

if strcmp(Taps, 'No') == 1
Results(1) = CO2_massFlux;
Results(2) = mean(Pressure_Ratio);
CELLS = num2cell(Results);
clipboard('copy', sprintf('% .20f\t%.20f', CELLS{1},CELLS{2}))
fprintf('Cd = %.4f\n', Cd)
```

Mapping out each sampling valve position

```
elseif strcmp(Taps, '10') == 1
if strcmp(Geometry, 'Sweeping_Jet', 12) == 1
Test_list = {' 7. 1. 1'
'11. 1. 1'
'15. 1. 1'
'16. 4. 1'
'16. 8. 1'
'16.12. 1'
'16.16. 1'
'16.16. 5'
'16.16. 9'
'16.16.11'
'16.16.12'};
CO2_massFluxM = LowSpeedCO2MassFlowRateIbs.Data./ (pi*(0.0686/2)^2*1);
else

Test_list = {' 2. 1. 1'
' 7. 1. 1'
'11. 1. 1'
'15. 1. 1'
'16. 4. 1'
```

```

    '16. 8. 1'
    '16.12. 1'
    '16.16. 1'
    '16.16. 5'
    '16.16. 9'
    '16.16.11'
    '16.16.12'};
CO2_massFluxM = LowSpeedCO2MassFlowRateIbs.Data./(pi*(0.1/2)^2*7);
end

Port_row_Spacing = 0.5; % in inches
D = 0.1; % Hole Diameter
Palte_port_Dist = 1.65; % distance of the first Tap on the plate to the holes in
inches
coupon_port_Dist = 0.4; % distance of the tap on the coupon to the holes in inches

SV =
strcat(cellstr(num2str(SV1(:))),','. ',cellstr(num2str(SV2(:))),','. ',cellstr(num2str(SV3(:
))));
Sample_Number = (1/LowSpeedGas_AnalyzerMean.Property.wf_increment)*Averaged_Smaples;

```

Assigning the sampling valve ports to their respective names

```

AirPlen = AveragePort('16.16.12',Sample_Number,SV,Gas_Analyzer);
CO2plen = AveragePort('16.16.11',Sample_Number,SV,Gas_Analyzer);

for i = 1:size(Test_list)-2

    CO2_Percent(i) = AveragePort(Test_list(i),Sample_Number,SV,Gas_Analyzer);
    P_ratio(i) = AveragePort(Test_list(i),Sample_Number,SV,Pressure_Ratio);
    P_Baro2(i) = AveragePort(Test_list(i),Sample_Number,SV,Pbaro);
    CO2_massFlux(i) = AveragePort(Test_list(i),Sample_Number,SV,CO2_massFluxM);
    CO2_mdot(i) = AveragePort(Test_list(i),Sample_Number,SV,CO2_massFlow);
    P_CO2_M = AveragePort(Test_list(i),Sample_Number,SV,P_CO2);
    T_CO2_M = AveragePort(Test_list(i),Sample_Number,SV,T_CO2);
    I(i) = AveragePort(Test_list(i),Sample_Number,SV,I_Matrix);
end

Test_List_ports = Test_list(1:size(Test_list,1)-4);

row_Names = {num2str(coupon_port_Dist/D)
num2str(Palte_port_Dist/D)};

Results(1) = mean(CO2_massFlux);
Results(2) = mean(P_ratio);
CELLS = num2cell(Results);
clipboard('copy', sprintf('%%.20f\t%.20f', CELLS{1},CELLS{2}))

```

Calculating eta from gas analysis

```

RCO2 = 44.0095;

```

```

W_CO2 = RCO2;

W_air = 28.9652; % molecular weight of air
W_O2 = 15.9994; % molecular weight of O2
Rair = 28.97 - (AirPlen * 44.01);
X_O2air = 0.209476; % assumed molar fraction of oxygen in air
CO2_Percent = CO2_Percent./100;
O2_Percent = (1-CO2_Percent) .* X_O2air;
X_airwall = O2_Percent ./ X_O2air; % molar fraction of air at the wall
W_w = (1 - X_airwall) .* W_CO2 + X_airwall .* W_air; % molecular weight of the mixture
at the wall
X_O2c = X_O2air * (1-CO2plen); % molar fraction of O2 at coolant plenum
X_airc = CO2plen / X_O2air; % molar fraction of air at coolant plenum
W_c = (CO2plen * W_CO2) + (X_airc * W_air); % molecular weight of the coolant gas
mixture
C_O2wall = O2_Percent .* W_O2 ./ W_w; %mass fraction of CO2 at wall
C_O2air = X_O2air * W_O2 / W_air; %mass fraction of CO2 at air plenum
C_O2coolant = X_O2c * W_O2 / W_c; %mass fraction of CO2 at coolant plenum
eta_ports2 = 1-1 ./ (1 + (X_O2air ./ O2_Percent - 1) .* (W_w ./ W_air)); %eta
eta_ports2 = eta_ports2';
eta_ports2(:,2) = eta_ports2;

if strcmp(Taps,'3') == 1
eta_ports2(:,1) = [4;31.66;56.76];
elseif strcmp(Taps,'10') == 1

eta_ports2(:,1) = [4
16.6
21.62
26.64
31.66
36.68
41.7
46.72
51.74
56.76];

end

```

Writing a file that contains eta from gas analysis along with the locations of ports as a multiple of film hole diameter

```

fID = fopen(filename_mean_eta,'wt');
Header = {strcat('VARIABLES = "Y/D"'),...
' "<greek>h</greek> Gas Analysis"',...
strcat('ZONE T="',Geometry,' BR ',BR,'")');
fprintf(fID,'%s\n',Header{1},Header{2},Header{3});
fclose(fID);
dlmwrite(filename_mean_eta,eta_ports2,'-append','delimiter',' ','precision','%0.13f');

```

Calculating SCFM of coolant and flow coefficient (Cv)

```

Baro_P = AveragePortRange(Test_list(size(Test_list,1)),Test_list(1),SV,Pbaro);
P_Test_section =
AveragePortRange(Test_list(size(Test_list,1)),Test_list(1),SV,P_test)/0.000145037738;
T_Test_section =
(AveragePortRange(Test_list(size(Test_list,1)),Test_list(1),SV,T_test) - 32) * 5/9;
CO2plen = CO2plen;
AirPlen = AirPlen;
CO2_Percent = CO2_Percent';
CO2_Percent = CO2_Percent
Port1 = Tag_out(Test_list(1),SV);
TimeLength =
LowSpeedGas_AnalyzerMean.Property.wf_increment*LowSpeedGas_AnalyzerMean.Total_Samples;
Time = linspace(0,TimeLength,LowSpeedTestSectionMach.Total_Samples);
P_ratio = P_ratio';
Pressure_Ratio2 = mean(P_ratio);
PR2 = mean(P_ratio);
CO2_mdots = mean(CO2_mdots);
P_CO2_val = mean(P_CO2_M);
T_CO2_val = mean(T_CO2_M);
gamCO2 = 1.28;
PRCrtit = (2/(gamCO2 +1))^(gamCO2 /(gamCO2 -1));
Pressure_Ratio2 = 1/Pressure_Ratio2;
Sg = 1.5189;
SCFM = (1/0.1234) * CO2_mdots * 60;
if PRCrtit >= Pressure_Ratio2 % Choked Flow
    Cv = SCFM / (13.61 * sqrt(1/(Sg * (T_CO2_val + 460.67)))));

else

    Cv = SCFM / (16.05 * sqrt(((P_CO2_val + Baro_P)^2 - Baro_P^2)/(Sg * (T_CO2_val +
460.67)))));

end

CO2_Percent =

0.475290885889399
0.188597816997934
0.140134126480821
0.110702140281589
0.090480436762678
0.074925756267661
0.067351225056196
0.058431684997607
0.053061575816048
0.048822419932101

```

Calculating discharge coefficient

```
mean(I);
```

```

FFT2 = sqrt((gc*g_CO2)/Rco2) *...
    sqrt((2/(g_CO2-1))*PR2^(-(g_CO2+1)/g_CO2))*(PR2^(((g_CO2-1)/g_CO2)-1));
Ae = (CO2_mdotsqrt(T_CO2_M+459.67))/((P_CO2_val + mean(P_Baro2))*144)*FFT2;
Cd = Ae/Aco2;
fprintf('Cd = %.4f\n', Cd)

```

```

Cd = 0.6043

```

```

end

```

```

Results(1) = mean(I_Matrix);
Results(2) = mean(CO2_massFlux);
Results(3) = mean(Pressure_Ratio);

```

```

CELLS = num2cell(Results);
clipboard('copy', sprintf('%.20f\t%.20f\t%.20f', CELLS{1}, CELLS{2}, CELLS{3}))

```

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APPENDIX A3: LABVIEW DATA ACQUISITION SYSTEM

Multiple LabVIEW codes were developed to monitor, log and calculate experimental parameters. Table 11 provides a description of each parameter along with its virtual and physical channel numbers.

Table 11 Acquired signals by the Data Acquisition System

virtual channel #	Chassis #	Channel #	Parameter	signal type	signal range	Scalar value	Zero shift value	Channel units
00	3	1	Mainstream sonic nozzle upstream pressure	Voltage	0-5 v	30	0.068163	psig
01	3	2	Mainstream sonic nozzle downstream pressure	Voltage	0-5 v	50	-1.22345	psig
02	4	1	Air Plenum Pressure	Voltage	0-5 v	30	0.232312	psig
03	3	3	Coolant sonic nozzle upstream pressure	Voltage	0-5 v	26	-0.152636	psig
04	4	0	Coolant sonic nozzle downstream pressure	Voltage	0-5 v	50	-1.175551	psig
05	7	0	Mainstream sonic nozzle upstream temperature	thermocouple	0-30 mv	N/A	N/A	degF
06	7	1	Coolant sonic nozzle upstream temperature	thermocouple	0-30 mv	N/A	N/A	degF
07	3	0	Barometric pressure	Voltage	0-5 v	1.2	10	psia
08	7	2	Air Plenum temperature	thermocouple	0-30 mv	N/A	N/A	degF
09	4	2	Supply pressure before air line regulator	Voltage	0-5 v	50	-1.175551	psig
10	1	0	Gas Analyzer CO ₂ %	Current	4-20 mA	6.25	-25	CO ₂ %
11	4	3	High pressure tank pressure level	Voltage	0-5 v	1000		psig
12	5	0	Coolant plenum pressure	Voltage	0-5 v	26	0.059437	psig
13	7	3	Coolant Plenum temperature	thermocouple	0-30 mv	N/A	N/A	degF

The signal for non thermocouple sensors is multiplied by the scalar value then the resulting value is added to the zero shift value resulting in engineering units. The results are recorded for the entire duration of the tests. The mass flow rates are calculated as described in

section 2.2. To run a test there are various steps that need to be taken. The following paragraphs will take the reader through those steps.

The operator needs to open the “Sampling Valves(3).vi” LabVIEW code. This vi opens the communication gate between the sampling valves and the PC. Next the run button has to be pressed (Ctrl+r). The dials show the position of each valve as it is being read from the USB communication gate. The operator can now minimize this window as it only needs to run in the background. The needed parameters such as the sampling valve drive port (the command to tell the sampling valve which port it needs to go to) and sampling valve status port (the current port number of each sampling valve) are communicated using global variables employing another virtual instrument (vi) or LabVIEW code.

Figure 77 Sampling valve communication vi

Figure 78 Status Display vi

The “status display.vi” code is a convenient way for the operator to monitor the test conditions while adjusting the mainstream flow and coolant flow regulators. This vi can be placed on a second monitor and the monitor can be turned to face the operator for simultaneous monitoring of the test conditions while applying adjustments to the mainstream and coolant flows. To the top left the blowing ratio is displayed with a meter with its digital value being displayed to the bottom right of the meter. Right below the digital display, another digital display with the tag “PR” is visible. This outputs the coolant plenum to mainstream flow pressure ratio. To the top right the mainstream Mach number value is displayed with the mainstream mass flow rate being shown below its digital meter (tagged as “Mass Flow”). To the bottom left a column is visible with the graduated values from 400 to 1500. This shows the high pressure tank level in psig. 400 psig is the lowest useful pressure for the tests performed in the present study. The LED button to the center labeled as “REC” is turned on whenever data is being recorded. There are target LED buttons both for BR and Mach. If each respective value is within 1% of the specified

target value the large LEDs turn on. If not either low or high LEDs will turn on depending whether the measured value is bigger or smaller than the target value. To the bottom right a chart with its digital value can be seen. The chart displays whatever parameter is selected from the range of available parameters in the main vi.

Next a text file called “GEA Film_Cooling_RecordData_Config.ini” needs to be opened. This is called the config file and it governs the sensor information that the main vi uses and data file parameters. The field in front of “fiSaveName =” needs to be changed to the appropriate test parameters. This is the file name that is going to be used to save the LabVIEW output (*.tdms). Other parameters such as “fiTitle =”, “fiSavePath =” and “fiAuthor =” can be changed to reflect the desired outcome. After the desired changes have taken place the file needs to be saved.

Figure 79 Main vi

Upon opening the “film cooling main.vi” a file open dialogue appears that prompts the user to open the appropriate config file. Once the config file is loaded, the vi starts to run. The

top portion of the vi is where the essential operating parameters lie. Starting from the top right, the drop down menu tagged as “Air nozzle Dia.” needs to be set to the size of the mainstream sonic nozzle installed. Failure to do so will result in wrong mainstream mass flow calculations and subsequently incorrect Mach number and BR calculations. The LED button tagged as “Automated?” will be in de-pressed mode when starting the vi. The operator can manually start recording test data by pressing the “WRITE TO FILE” button. When the button is de-pressed the recording will be stopped. To the left, the drop down menu tagged as “CO2 nozzle Dia.” needs to be set to the appropriate size of the coolant sonic nozzle installed. Failure to do so will result in wrong coolant mass flow calculations and subsequently incorrect BR calculations. To the top left, there are two number boxes tagged as “#of holes” and “Hole Diameter (in)”. The coolant area calculation is carried out by calculating area of a circle using its diameter in inches then multiplying it by the number of film cooling holes. Failure to input the correct values will result in wrong BR calculations. To the top center, a large text box tagged “Output File Path” shows the file path of the output file. It is advisable to double check this to make sure the correct file name was chosen. To the bottom left of the “CO2 Nozzle Dia.” drop down menu, the LED button tagged as “Keil Probe Calculation?” needs to be de-pressed. To its right, the number box tagged as “Target Mach” is the target Mach value to be entered by the operator. For the present study a value of 0.3 was used. To the bottom right a column tagged as “Desired Analyzer Flow Rate (L/m)” indicates the sample gas flow rate that the gas analyzer needs to apply by adjusting its internal pump. The meter tagged as “Pressure ratio” shows the coolant plenum to mainstream flow pressure ratio. To the left of the screen text boxes tagged as “Vair” and “Vc” show the mainstream flow and coolant flow velocities respectively. The text box tagged as “I” shows the value of momentum flux ratio. On the top center a chart can continuously plot different variables

vs time. To choose which parameter to be plotted, the drop down menu to its top left tagged as “Graph Selection” is employed. A text box to the top of the graph displays what variable is currently being plotted. Another text box to the top right of the graph shows the instantaneous value being plotted. The plot resulting from this graph will be displayed on the chart contained in the “Status Display.vi” code. The left bottom side of the screen features 3 dials and gauges. The dials can be used to manually change the position of the sampling valves and the gauges show the current position of each valve. If the LED button tagged as “Automated?” (top right of the screen) is pressed, the operator can no longer control the sampling valves and “WRITE TO FILE” manually. The values for the mentioned parameters will be controlled by a vi called “Global Valve Drive PSP – Selective II.vi”.

Figure 80 Automated vi used to drive sampling valves

The number box on the top left tagged as “Record Timer (min)” is used to set how long each gas port is recorded (typically 3 minutes). “Air Start Record (min)” is the amount of time the air plenum sample gas at the beginning of the experiment gets recorded (typically 3 minutes) and “Air End Record (min)” is the amount of time the air plenum sample gas at the end of the experiment gets recorded (typically 12 minutes). This is to quantify the gas analyzer measurement drift. “CO2 Start Record (min)” and “CO2 End Record (min)” are typically set to 5 minutes. The LED button tagged as “Automated Recording?” needs to be pressed at all times. To the bottom left a checkbox matrix enables the operator to select which ports are switched to by the sampling valves according to the convention on Figure 81.

Figure 81 Port selection convention followed by the automated vi

Once proper selection has been applied and verified, the operator needs to press the “Automated?” LED button on the “Film Cooling Main.vi” and then run the “Global Valve Drive

– Selective II.vi”. The code then automatically records the data switching through the appropriate ports. The “Global Valve Drive – Selective II.vi” code also shows the current port being recorded by activating the appropriate LED to the right of the checkbox matrix. Once all the ports are recorded, the “Global Valve Drive – Selective II.vi” code will de-press the “WRITE TO FILE” button and the recording stops. To stop the “Film Cooling Main.vi” without the loss of data, the red button tagged as “STOP APPLICATION” must be pressed. Failure to do so results in loss of ALL recorded data.

APPENDIX A4: UNCERTAINTY DETAILS

The following section is mainly quotes from [58] and [59] to clarify the uncertainty calculations. The numbers associated with each step of the uncertainty analysis will be presented in tables.

The result R of an experiment is assumed to be calculated from a set of measurements using a data interpretation program represented by:

$$R = R(X_1, X_2, X_3, \dots, X_N)$$

Each measurement has a known bias limit and precision index, and the number of degrees of freedom for each precision index is known. The first step in estimating the overall uncertainty in the result is to calculate the bias limit and the precision index of the result. The bias limit of each measurement affects the bias limit of the calculated result in proportion to its sensitivity coefficient (the partial derivative of R with respect to X_i is the sensitivity coefficient of the result R with respect to the measurement X_i). If only one measurement has a nonzero bias limit, the bias limit of the result would be:

$$B_{R,i} = \frac{\partial R}{\partial X_i} B_i$$

When several independent variables are used in the function R , the individual terms are combined by a root-sum-square method:

$$B_R = \left\{ \sum_{i=1}^N \left(\frac{\partial R}{\partial X_i} B_i \right)^2 \right\}^{1/2}$$

MACH UNCERTAINTY:

	Var	instrument rating	calculated uncertainty	Uncertainty +	Uncertainty -	Mach_0
Pair	23.712	0.15	0.061	0.15	-0.15	0.29949258
Pbaro	14.3792	0.006	0.0005	0.006	-0.006	
P_Plen	1.4067	0.15	0.012	0.15	-0.15	
Tair	504.155	0.3	0.3	0.3	-0.3	
Tplen	513.1766	0.3	0.3	0.3	-0.3	
A	0.041667					
R	53.28786					
gc	32.2					
gamma	1.4					
a	0.678938					
b	2.46E-05					
c	-0.00598					

Pair	Pbaro	P_Plen	Tair	Tplen	Mach i+	Ci+
23.862	14.3792	1.4067	504.155	513.1766	0.300674	0.001182
23.712	14.3852	1.4067	504.155	513.1766	0.299426	-6.7E-05
23.712	14.3792	1.5567	504.155	513.1766	0.296674	-0.00282
23.712	14.3792	1.4067	504.455	513.1766	0.299404	-8.9E-05
23.712	14.3792	1.4067	504.155	513.4766	0.29958	8.75E-05
Pair	Pbaro	P_Plen	Tair	Tplen	Mach i-	Ci-
23.562	14.3792	1.4067	504.155	513.1766	0.298311	-0.00118
23.712	14.3732	1.4067	504.155	513.1766	0.299559	6.66E-05
23.712	14.3792	1.2567	504.155	513.1766	0.302366	0.002873
23.712	14.3792	1.4067	503.855	513.1766	0.299582	8.91E-05
23.712	14.3792	1.4067	504.155	512.8766	0.299405	-8.8E-05
Ci						
0.001182	1.39676E-06					
6.66E-05	4.43013E-09					
0.002846	8.10017E-06					
8.91E-05	7.94011E-09					
8.75E-05	7.66339E-09					
	0.003084958					
	0.010300615					
	1.030061457					
	1%					

BLOWING RATIO UNCERTAINTY

	Var	instrument rating	calculated uncertainty	Uncertainty +	Uncertainty -	BR_0
Pair	23.712	0.15	0.0422	0.15	-0.15	0.99733
Pbaro	14.3792	0.006	0.0005	0.006	-0.006	
P_CO2	16.0983	0.13	0.014	0.13	-0.13	
Tair	504.155	0.3	0.0743	0.3	-0.3	
TCO2	507.8398	0.3	0.1007	0.3	-0.3	
A CO2	0.000382					
A air	0.041667					
R	53.28786					
gc	32.2					
gamma	1.4					
a	0.678938					
b	2.46E-05					
c	-0.00598					
a co2	0.007758					
b co2	1.46E-06					
c co2	-1.11E-04					
Pair	Pbaro	P_CO2	Tair	TCO2	BR i+	Ci+
23.862	14.3792	16.0983	504.155	507.8398	0.99341	-0.00392
23.712	14.3852	16.0983	504.155	507.8398	0.99737	4.03E-05
23.712	14.3792	16.2283	504.155	507.8398	1.001614	0.004284
23.712	14.3792	16.0983	504.455	507.8398	0.997627	0.000297
23.712	14.3792	16.0983	504.155	508.1398	0.997036	-0.00029
Pair	Pbaro	P_CO2	Tair	TCO2	BR i-	Ci-
23.562	14.3792	16.0983	504.155	507.8398	1.001281	0.003951
23.712	14.3732	16.0983	504.155	507.8398	0.99729	-4E-05
23.712	14.3792	15.9683	504.155	507.8398	0.993046	-0.00428
23.712	14.3792	16.0983	503.855	507.8398	0.997033	-0.0003
23.712	14.3792	16.0983	504.155	507.5398	0.997625	0.000295
Ci	Ci ²					
0.003936	1.55E-05					
4.03E-05	1.62E-09					
0.004284	1.84E-05					
0.000297	8.81E-08					
0.000295	8.68E-08					
	0.005832					
	0.005848					
	0.584806					
	0.6	%				

DISCHARGE COEFFICIENT UNCERTAINTY

mdot co2	Ae	Cd	Pco2_plen	Pbaro	P_CO2	TCO2	
0.010525	0.00023	0.601677	2.1249	14.3792	16.0983	507.8398	
			1.9949	14.3852	16.0983	507.8398	
			1.9949	14.3792	16.2283	507.8398	
			1.9949	14.3792	16.0983	508.1398	
			Pco2_plen	Pbaro	P_CO2	TCO2	
			1.8649	14.3792	16.0983	507.8398	
			1.9949	14.3732	16.0983	507.8398	
			1.9949	14.3792	15.9683	507.8398	
			1.9949	14.3792	16.0983	507.5398	
PR i+ Ci+	PR i+	FFT i+	mdot co2 i+ Ci+	mdot co2 i+	Ae i+	Cd i+	Ci+
0.009041	1.147776	0.448067	0	0.010525111	0.000223	0.583402	-0.01827
-5.8E-05	1.138677	0.43784	2.08656E-06	0.010527198	0.00023	0.601668	-9E-06
0	1.138735	0.437907	4.52099E-05	0.010570321	0.000231	0.604261	0.002584
0	1.138735	0.437907	-3.10741E-06	0.010522004	0.00023	0.601677	0
PR i- Ci-	PR i-	FFT i-	mdot co2 i- Ci-	mdot co2 i-	Ae i-	Cd i-	Ci-
-0.00904	1.129694	0.427096	0	0.010525111	0.000237	0.621843	0.020167
5.79E-05	1.138793	0.437974	-2.08655E-06	0.010523025	0.00023	0.601686	9.05E-06
0	1.138735	0.437907	-4.52075E-05	0.010479904	0.000229	0.599092	-0.00258
0	1.138735	0.437907	3.11017E-06	0.010528221	0.00023	0.601677	0
	Ci	Ci ²					
	0.019221	0.000369					
	9.04E-06	8.17E-11					
	0.002584	6.68E-06					
	0	0					
		0.019394					
		0.032233					
		3.223293					
		3.2 %					

FILM EFFECTIVENESS UNCERTAINTY

Given a functional relationship of the form $y = y(x_1, x_2, \dots, x_i)$ the general equation for propagation of errors based on the linearized Taylor series expansion is:

$$\sigma_y^2 = \sigma_{x_1}^2 \left(\frac{\partial y}{\partial x_1} \right)^2 + \sigma_{x_2}^2 \left(\frac{\partial y}{\partial x_2} \right)^2 + 2\sigma_{x_1 x_2} \left(\frac{\partial y}{\partial x_1} \right) \left(\frac{\partial y}{\partial x_2} \right)$$

The linearization process is based on the assumptions the errors are small and the influence coefficients (partial derivatives) are nearly constant. This equation will be used throughout the uncertainty analysis to determine the effect of various sources of noise on the quantity of interest. Three points are worth noting. First, the elemental errors may be of the random or bias nature. Second, unless explicitly stated it is assumed all error sources are independent or nearly independent so all cross correlation terms are zero or negligible. Third, the combination of elemental precision and bias errors to give the total uncertainty will be based on the Root-Sum-Square (RSS) method:

$$(U_{RSS})^2 = (U_{bias})^2 + \left(\frac{2U_{Random}}{\sqrt{m}} \right)^2$$

Where m is the number of samples averaged. This combination corresponds to a 95% coverage level when the bias and random error components are added by the Root-Mean-Square (RMS) method corresponding to a 95% confidence level.

The uncertainty caused by CCD pixel-to-pixel non-uniformity is also known as scene noise. It is not noise in the classical sense that may be attributed to a single pixel, but rather in its effect on an image recorded by a group of pixels. The non-uniformity may be due to several

factors of which the most significant are the physical dimensions and doping concentration of each pixel. The resulting effect of this non-uniformity is that each pixel will have a different response to an excitation energy source. Considering a CCD exposed to a uniform source, the following would be observed. First, the image would have a random deviation centered about some mean pixel value due to photon shot noise. Second, the image would also have a non-random variation coinciding with the CCD pattern of non-uniformity. Thus, realizing that the image or scene should correspond to the uniformity of the excitation source, the total noise including the photon shot and scene noise is:

$$(dI)^2 = (\sqrt{S})^2 + (XS)^2$$

Where S and X correspond to the measured signal and level of pixel-to-pixel variation, respectively. Realizing that I and S are synonymous the above EQ can be written as:

$$\left(\frac{dI}{I}\right)^2 = \left(\frac{\sqrt{S}}{S}\right)^2 + \left(\frac{XS}{S}\right)^2 = \frac{1}{S} + X^2$$

$$\frac{1}{S} = \left(\frac{1}{SNR_{SHOT}}\right)^2; \quad X^2 = \left(\frac{1}{SNR_{SCENE}}\right)^2$$

The RSS form in terms of SNR can be written as:

$$\left(\frac{1}{SNR_{\bar{T}}}\right)^2 = \frac{4}{m} \left(\frac{1}{SNR_{SHOT}}\right)^2 + \left(\frac{1}{SNR_{SCENE}}\right)^2$$

Where $\bar{T}$ indicates the total image SNR includes an averaged random component. It is apparent that for large signals the scene noise dominates the total image uncertainty and that frame (image) averaging is ineffectual. For our case the lowest SNR (shot noise to signal ratio) is

25. The uncertainty of the gas analyzer is 0.04%. The SNR was propagated through the intensity ratio expression at the range close to the film holes and far away from the film holes:

near the holes ($-4 < Y/D < 10$)						
1/SNR	I ref off	I ref on	I sig off	I sig on	I ratio	
0.066667	6520.5	6632.93	9985.66	12631.5	0.80416721	
	6955.2	6632.93	9985.66	12631.5	0.75390676	-0.050260451
	6520.5	7075.125	9985.66	12631.5	0.85777836	0.053611148
	6520.5	6632.93	10651.37	12631.5	0.85777836	0.053611148
	6520.5	6632.93	9985.66	13473.6	0.75390676	-0.050260451
						0.010800536
						0.013430709
						1.3%
downstream ($50 < Y/D < 78$)						
Dark Current	I ref off	I ref on	I sig off	I sig on	I ratio	
0.1	12678.8	12632.4	24556.7	25577.6	0.95657259	
	13946.68	12632.4	24556.7	25577.6	0.86961144	-0.086961144
	12678.8	13895.64	24556.7	25577.6	1.05222985	0.095657259
	12678.8	12632.4	27012.37	25577.6	1.05222985	0.095657259
	12678.8	12632.4	24556.7	28135.36	0.86961144	-0.086961144
						0.033425104
						0.034942569
						3.5%

It is observed that the image intensity ratio uncertainty is 1.3% near the holes and 3.5% far away from the holes. This is propagated through the calibration procedure and the following shift in effectiveness is recorded:

Shift in η		
	near the holes ($-4 < Y/D < 10$)	downstream ($50 < Y/D < 78$)
gas analysis	0.008450834	0.002024676
CCD SNR	0.128798049	-0.044480603
	Ci	Ci
	0.025242434	0.059829475
	2.524243408	5.982947485
	2.52%	5.98%

APPENDIX A5: PART NUMBERS

Item	Part number	distributor
Air line regulator	R18-C05-RGLA	Norgren, Inc.
Air Plenum Pressure	A50G3-TA-A2-CA-H0-PF	GE Measurement & Control
Air Plenum temperature	HKMQIN-125U-6	Omega Engineering, Inc.
Barometric pressure	A50G3-TA-A2-CA-H0-PF	GE Measurement & Control
Coolant line regulator	11-002-061	Norgren, Inc.
Coolant plenum pressure	A50G3-TA-A2-CA-H0-PF	GE Measurement & Control
Coolant Plenum temperature	HKMQIN-125U-6	Omega Engineering, Inc.
Coolant sonic nozzle	SN08-SA-125	FlowMaxx Engineering
Coolant sonic nozzle downstream pressure	A50G3-TA-A1-CA-H0-PF	GE Measurement & Control
Coolant sonic nozzle upstream pressure	A50G3-TA-A2-CA-H0-PF	GE Measurement & Control
Coolant sonic nozzle upstream temperature	HKMQIN-125U-6	Omega Engineering, Inc.
FIB base coat	FB-400	ISSI
FIB binary paint	BF-400	ISSI
Gas Analyzer CO2%	7MB2335-3CR00-5AA1	ApplyTech, Inc.
Gas sampling valve	EUTB-CSD16MWE	VALCO INSTRUMENTS CO.,INC.
Gas sampling valve ferrules	ZF1-10	VALCO INSTRUMENTS CO.,INC.
Long metal tubing	T5C40-50	VALCO INSTRUMENTS CO.,INC.
Mainstream sonic nozzle	SN32-SA-1250	FlowMaxx Engineering
Mainstream sonic nozzle downstream pressure	A50G3-TA-A1-CA-H0-PF	GE Measurement & Control
Mainstream sonic nozzle upstream pressure	A50G3-TA-A2-CA-H0-PF	GE Measurement & Control
Mainstream sonic nozzle upstream temperature	HKMQIN-125U-6	Omega Engineering, Inc.
National Instruments Data Acquisition chassis	cDAQ-9178	National Instruments
National Instruments Data Acquisition module	NI 9215 BNC	National Instruments
National Instruments Data Acquisition module	NI 9203 Screw Terminal	National Instruments
National Instruments Data Acquisition module	NI 9927	National Instruments
National Instruments Data Acquisition module	NI 9211	National Instruments
National Instruments Data Acquisition module	NI 9401	National Instruments
Pressure transducer connectors female	A97647-ND	www.digikey.com
Pressure transducer connectors male	A97644-ND	www.digikey.com
Short metal tubing	TUBN-063 Bulged S.S.	Scanivalve
Supply pressure before air line regulator	A50G3-TA-A1-CA-H0-PF	GE Measurement & Control
Thermocouple connectors: male + female	GMP-K-MF	Omega Engineering, Inc.
Type K thermocouple wires	TT-K-24-SLE-200	Omega Engineering, Inc.

APPENDIX A6: DRAWINGS

Drawings were prepared partially by Mouleeswaran Kandampalayam Kandasamy Palaniappan.