Simulations of Multiphase Particle Deposition on Endwall Film-Cooling

Demand for clean energy has increased motivation to design gas turbines capable of burning alternative fuels such as coal derived synthesis gas (syngas). One challenge associated with burning coal derived syngas is that trace amounts of particulate matter in the fuel and air can deposit on turbine hardware reducing the effectiveness of film-cooling. For the current study, a method was developed to dynamically simulate multiphase particle deposition through injection of a low melting melting wax. The method was developed so the effects of deposition on endwall film-cooling could be quantified using a large scale vane cascade in a low speed wind tunnel. Microcrystalline wax was injected into the mainstream flow using atomizing spray nozzles to simulate both solid and molten particulate matter in a turbine gas path. Infrared thermography was used to quantify cooling effectiveness with and without deposition at various locations on a film-cooled endwall. Measured results indicated reductions in adiabatic effectiveness by as much as 30% whereby the reduction was highly dependent on the location of the film-cooling holes relative to the vane. [DOI: 10.1115/1.4002962]

1 Introduction

Utilizing available coal resources to efficiently generate power while minimizing the production of greenhouse gases has become a major challenge for the current generation of engineers. Among the methods that exist for utilizing available coal resources in a clean manner is coal gasification. Integrated gasification combined cycle (IGCC) power plants utilize coal gasification technology to produce hydrogen and carbon monoxide based synthesis gas (syngas) that can be combusted in a combined cycle gas turbine power system.

A major challenge associated with gas turbine design is developing cooling technologies for turbine components that operate at temperatures above material melting limits. Turbine components must be cooled to withstand mechanical stresses that are exacerbated by the extreme temperatures and pressures that exist in the turbine section. In addition, particles as large as 10 μm that originate from the fuel and air supply can create a potential hazard by depositing on turbine components and impairing sophisticated cooling technologies such as film-cooling. It is essential to understand how particle deposition occurs so that film-cooling designs can be developed to mitigate the negative effects of deposition. Because full engine tests are costly, methods for simulating deposition in a laboratory setting are needed.

The region most susceptible to the negative effects of particle deposition is the first stage vane where gas temperatures are highest and the largest particles are most likely to deposit because of their molten state. For the current study, particle deposition is simulated dynamically using wax in a large scale turbine vane cascade. Lawson and Thole [1] showed that deposition is highly dependent on whether a particle is in solid or molten form upon impacting the surface. Deposition is simulated at different thermal conditions to observe how deposition develops. The effects of deposition on endwall film-cooling are quantified using infrared (IR) thermography to measure surface temperatures and thereby calculate adiabatic effectiveness in a spatially resolved manner.

2 Review of Relevant Literature

The idea of shifting to alternative fuels has led to numerous studies related to the effects of deposition on turbine cooling. These studies can be categorized based on the methods used to mimic surface deposition. One method used to mimic surface deposition was to condition a surface with deposits based on surface measurements from actual turbine hardware. Cardwell et al. [2], Sundaram and Thole [3], and Somawardhana and Bogard [4] conducted studies related to the effects of roughness on airfoil and endwall cooling relevant to gas turbines for which roughness simulations were based on turbine hardware measurements made by Bons et al. [5].

Cardwell et al. [2] simulated roughness on a film-cooled endwall using sandpaper on a large scale turbine airfoil platform to model the roughness measured by Bons et al. [5]. By measuring adiabatic effectiveness at various blowing ratios, Cardwell et al. [2] determined that roughness had little-to-no effect on cooling at low blowing ratios but caused a decrease in cooling effectiveness at high blowing ratios because of the thick boundary layer promoted by the roughened surface.

An extensive study was conducted by Sundaram and Thole [3] to determine the effects of deposition on endwall film-cooling near the leading edge of a nozzle guide vane. Sundaram and Thole [3] manufactured deposits of ideal two-dimensional shapes and sizes based on measurements made by Bons et al. [5]. They found that small deposits placed downstream of leading edge cooling holes actually enhanced cooling effectiveness by 25% for a deposit height of 0.5D and a blowing ratio of 1.5.

Somawardhana and Bogard [4] conducted a study to determine the effects of varying surface roughness and near-hole obstructions on adiabatic effectiveness. Similar to the methods used by Sundaram and Thole [3], Somawardhana and Bogard [4] placed idealized obstructions upstream and downstream of film-cooling holes to simulate deposits caused by large agglomerations of particles that could deposit randomly. The reduction of cooling performance due to deposition was highly dependent on blowing ratio and the location of the deposits relative to the cooling holes. Deposition caused as much as a 30% reduction in adiabatic effectiveness at low blowing ratios and a 30% improvement in adiabatic effectiveness at high blowing ratios. In addition, Somawardhana and Bogard [4] showed that obstructions placed upstream of...
film-cooling holes reduced adiabatic effectiveness while obstructions placed downstream of cooling holes could actually improve effectiveness.

Another method used to mimic surface deposition is dynamic simulation. Jensen et al. [6], Bons et al. [7], Crosby et al. [8], Ai et al. [9], and Lewis et al. [10] conducted studies in the Turbine Accelerated Deposition Facility (TADF) designed to dynamically simulate deposition also in a laboratory environment. These studies simulated particle deposition resulting from the combustion of various alternative fuels in land based gas turbines.

By increasing the concentration of particulate matter in the hot gas path, Jensen et al. [6] could simulate 10,000 h of turbine operation in a 4 h test. Bons et al. [7] observed deposition evolution by operating the TADF through multiple burn cycles for each coupon. By recreating roughness models in acrylic, they measured heat transfer at different stages in the deposition evolution. Through four burn cycles, they found that heat transfer coefficients increased by 27% relative to the smooth baseline. Crosby et al. [8] conducted tests in the TADF and found that deposition rate increased with an increase in particle size, an increase in gas temperature, and an increase in surface temperature.

Using the TADF, Ai et al. [9] concluded that increased deposit height resulted in increased surface temperatures. They found that an increase in blowing ratio decreased surface temperatures and reduced the amount of deposition in coolant wakes. Lewis et al. [10] recreated film-cooling models with deposition based on experiments conducted in the TADF. They found that cooling effectiveness was highest when deposition only existed upstream of the cooling holes.

A computational study was performed by Sreedharan and Tafti [11] to determine the effect of blowing ratio on deposition for a vane leading edge film-cooling geometry. They observed the deposition and erosive behavior of 5 μm and 7 μm ash particles and found that coolant jets were successful at minimizing leading edge deposition by cooling particles and pushing them away from the surface and preventing them from depositing. They found that an increase in blowing ratio from 0.5 to 2.0 increased deposition of 5 μm particles by 4% but decreased deposition of 7 μm particles by 5%.

Much has been learned from the deposition studies described above; however, dynamic simulation methods are missing in the presence of complex secondary flow structures that exist near endwalls of turbine cascades. Lawson and Thole [1] developed a method to simulate deposition dynamically in a laboratory environment at near standard temperature and pressure conditions (20°C and 101.325 kPa) using wax as the particulate. Wax was used to simulate deposition in the vicinity of a row of endwall cooling holes in a low speed wind tunnel. Lawson and Thole [1] found that downstream cooling effectiveness decreased and approached an equilibrium state as deposition is collected on the surface. They found that deposition reduced downstream effectiveness by as much as 25% at momentum flux ratios of 0.23 and 0.5 and only 6% at a momentum flux ratio of 0.95. Albert et al. [12] used a similar wax injection technique to simulate deposition dynamically on a vane leading edge model with film-cooling. Similar to Lawson and Thole [1], Albert et al. [12] found that deposition increased in time to reach a quasi-steady thickness. Albert et al. [12] also found that film-cooling blowing ratio and the difference between mainstream and wax solidification temperatures had a strong effect on deposition.

The objective of the current study was to further develop the wax deposition method used by Lawson and Thole [1]. The method was improved such that it could be used in a large scale turbine cascade to observe how deposition occurs on a film-cooled endwall under the influence of complex flow structures such as the leading edge vortex. The development of the wax simulation method was discussed, including environmental scanning electron microscope photos of fly ash deposition compared with wax deposition, in a previous paper published by the same authors of Lawson and Thole [1].

### 3 Experimental Methods

Experiments for the current study were conducted in the large scale turbine cascade model in The Pennsylvania State University Experimental and Computational Convection Laboratory (PSUExCCL). The turbine cascade test section was located in a closed loop wind tunnel shown in Fig. 1. Flow through the wind tunnel was supplied by a 50 hp axial fan. Downstream of the fan, the primary flow was cooled by a heat exchanger before dividing into two secondary coolant passages and a mainstream passage. The mainstream flow in the center passage was directed through a heater bank that increased the mainstream temperature to 328 K. The secondary flow passages were cooled to 298 K by heat exchangers to achieve a temperature difference between the primary and secondary air of 30 K. After passing through the heater bank, the mainstream flow was directed through a series of screens and flow straightening honeycomb. A turbulence grid located 3.6 chord lengths upstream of the vane cascade was used to achieve 4% mainstream turbulence intensity at the entrance to the vane cascade test section.

The turbine cascade test section consisted of two full passages with one center vane, a full neighboring vane, and a half neighboring vane. The vane geometry is a commercial vane described in detail by Radomsky and Thole [14]. The operating conditions and geometric specifications for the vane cascade are shown in Table 1. The inlet Reynolds number shown in Table 1 was matched with the engine operating conditions to scale the mainstream flow. A film-cooled endwall was constructed with low thermal conductivity polyurethane foam (k=0.033 W/m K) for which the specific cooling hole pattern designed by Knost and Thole [15] is shown in Fig. 2. For the current study, attention was focused specifically on the passage and leading edge cooling rows, as identified in Fig. 2. The passage row had a compound angle of 90 deg relative to the flow while the leading edge row had holes that were inline with the incoming flow direction. Low thermal conductivity foam was used to create an adiabatic wall condition so that adiabatic effectiveness measurements could be made. Wire mesh, window screen, and a filter were placed in the

![Fig. 1 Illustration of wind tunnel facility](image)

### Table 1 Geometric and flow conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>Scaled up chord length, C</td>
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<td>Pitch/chord, P/C</td>
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<tr>
<td>Span/chord, S/C</td>
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<td>Hole, L/D</td>
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<tr>
<td>Re_a</td>
<td>2.25 x 10^5</td>
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<tr>
<td>Inlet and exit angles</td>
<td>0 deg and 72 deg</td>
</tr>
<tr>
<td>Inlet, exit Mach number, M_a, M_x</td>
<td>0.012, 0.085</td>
</tr>
<tr>
<td>Inlet mainstream velocity, U_a</td>
<td>6.3 m/s</td>
</tr>
</tbody>
</table>

Transactions of the ASME
wind tunnel elbow section downstream of the test section and upstream of the fan to capture injected wax particles that passed through the test section.

For the current study, air from the top cooling passage was used to supply coolant to two separate plenums. One plenum was used to supply coolant to a two-dimensional flush slot angled 45 deg with the flow to simulate coolant flow through the combustor turbine interface. Another plenum was located beneath the endwall of the turbine cascade test section and was used to supply coolant to the endwall film-cooling holes, which were angled at 30 deg relative to the endwall surface. A variable speed blower located on top of the wind tunnel controlled the airflow to the coolant plenums and could be used to set the coolant flow conditions. Film-cooling flows were characterized by $M_{\text{ideal}}$ of the leading edge cooling hole upstream of the stagnation point. For every test conducted for the current study, the coolant to mainstream density ratio was 1.10.

### 3.1 Adiabatic Effectiveness Measurements

Steady state IR thermography was used to measure surface temperatures at various film-cooling operating conditions with and without deposition. Contrary to conventional methods in which surface temperature measurement resolution is limited by the number of thermocouples on the surface, a FLIR P20 IR camera was used to measure surface temperatures with high spatial resolution. IR images were acquired at five port locations perpendicular to the endwall surface. Each IR image had a resolution of 320 × 240 pixels and a viewing area of 24 × 18 cm² resulting in 715 μm (0.16D) resolution.

During experiments, thermocouple measurements were monitored periodically to determine when steady state was achieved. Upon reaching steady state for a given experiment (approximately 4 h), IR images were taken at each of the five port locations. At each port location, five images were acquired and calibrated using thermocouples placed in discrete locations on the endwall surface. Images were calibrated by adjusting the background temperature and emissivity until the IR temperatures matched the thermocouple measurements for each corresponding thermocouple location.

Although the endwall was constructed with low thermal conductivity foam, it was still necessary to apply a one-dimensional conduction correction described by Ethridge et al. [16]. To perform the conduction correction, cool air was supplied to the coolant plenums while the upstream slot and the film-cooling holes were blocked to prevent external surface cooling. By simulating the temperature difference between the external surface with no cooling and the internal surface exposed to the coolant air, a conduction correction could be imposed on the final effectiveness results. The spatially resolved correction indicated values as high as $\eta=0.12$ upstream of the test section and $\eta=0.06$ on the foam endwall areas. To apply a local correction, the spatially resolved values were subtracted from the measured values and normalized.

### 3.2 Uncertainty Analysis

An uncertainty analysis was performed for the blowing ratio, momentum flux ratio, and adiabatic effectiveness calculations using the uncertainty propagation method described by Moffat [17]. The blowing ratio uncertainty was $\pm 0.0218$ (2.1% at $M=1.0$) and the momentum flux ratio uncertainty was $\pm 0.0285$ (3.0% at $I=0.95$). Uncertainty in the adiabatic effectiveness measurements was directly attributable to the temperature measurement methods used. The bias uncertainty for thermocouples that were used to measure coolant jet and mainstream temperatures was 0.5°C while the precision uncertainty for thermocouple measurements was 0.12°C. The bias and precision uncertainties associated with the adiabatic wall temperatures measured by the IR camera were 0.51°C and 0.34°C, respectively. Adiabatic effectiveness uncertainty was $\pm 0.028$ at an $\eta$ value of 0.14 and $\pm 0.021$ at an $\eta$ value of 0.89.

### 3.3 Dynamic Deposition Simulation and Analysis

Deposition was simulated dynamically using a two nozzle wax injection system with both nozzles located at 33% span, as illustrated in Fig. 3. A stream of liquid wax was injected through the center of each nozzle head while two atomizing air jets aimed toward the wax stream served to break up the liquid wax into a mist of wax particles. A molten wax supply was stored in a heated reservoir and compressed air was used to pressurize the wax reservoir and supply atomizing air. Air and liquid regulators were used to control the atomizing air pressure and liquid wax flowrate independently. For a given wax flowrate, adjustment of the atomizing air pressure varied the particle size distribution. The atomizing air and heated wax lines were routed through the bars of the turbulence grid, which housed the two spray nozzles. The turbulence grid was located 3.6 chord lengths upstream of the vane row allowing adequate distance for the injected particles to be evenly distributed across the width of the vane row. Deposition patterns on the endwall were periodic across the span of the test section.

To simulate the aerodynamic properties of fly ash particles in an engine, it was necessary to match the Stokes number range between the laboratory and engine environments. A method similar to that used by Lawson and Thole [1] was used to determine that
wax particles in simulation conditions must be 10 times larger than fly ash particles in engine conditions to achieve the same particle trajectory, as shown in Fig. 4. Therefore, wax particles between $1/9262 \text{m}$ and $100/9262 \text{m}$ were required to simulate particle trajectories of $0.1–10/9262 \text{m}$ fly ash particles that exist in engine conditions. A Malvern Spraytec particle analyzer capable of characterizing aerosol droplets in the size range of $0.1–2000/9262 \text{m}$ was utilized to measure the size distribution of particles generated using the wax injection system. For a liquid wax pressure of $138 \text{kPa}$ ($20 \text{psi}$) that resulted in a wax flow rate of $1.9 \text{g/s}$ from each nozzle, particle sizes were measured for various atomizing air pressures. Figure 5 shows the particle size distribution for a liquid wax flow rate of $1.9 \text{g/s}$ at atomizing air pressures of $69 \text{kPa}$ ($10 \text{psi}$), $207 \text{kPa}$ ($30 \text{psi}$), $276 \text{kPa}$ ($40 \text{psi}$), and $414 \text{kPa}$ ($60 \text{psi}$). Increasing atomizing air pressure increased air jet velocity, which broke up the liquid stream and decreased particle size distribution. To achieve particle sizes less than the $100 \text{um}$ limit necessary to match Stokes number, the atomizing air pressure was set to $276 \text{kPa}$ with a liquid flowrate of $1.9 \text{g/s}$ from each nozzle for all deposition simulation experiments.

In addition to simulating particle trajectories, it was also desirable to simulate the thermal properties of particles that exist in engine conditions. Lawson and Thole concluded that the particle phase (solid or liquid) is of particular importance to deposition; therefore, it was necessary to scale the phase of fly ash as it exists in engine conditions. The time it takes a particle to solidify after the combustion process was chosen as the appropriate parameter to scale the phase change process. Biot numbers for fly ash particles and wax particles were calculated to be 0.2 and 0.04, respectively. Because the Biot number for both cases was much less than 1, a lumped mass approximation could be used to calculate temperature as a function of time for fly ash and wax particles. The solidification of a particle immersed in a fluid with constant temperature takes place in two separate processes. First, the temperature drops exponentially with time until it reaches the material solidification temperature. The time required for a particle to reach the material solidification temperature, $t_1$, can then be expressed by Eq. (1).

$$t_1 = -\frac{p C_p V_p}{h A_p} \ln \left( \frac{T_{p,s} - T}{T_{p,i} - T} \right)$$

Second, the temperature remains at the solidification temperature until the particle loses the equivalent of the latent heat of fusion to the surrounding gases. The time it takes for the particle to lose the heat necessary to change from liquid to solid, $t_2$, is shown in Eq. (2).

$$t_2 = \frac{\Delta h_{fus} p V_p}{h A_p (T_{p,s} - T_{p,i})}$$

To scale the solidification time from engine conditions to laboratory conditions, it is normalized by the time it takes the particle to travel from the injection location to the nozzle guide vane. The expression for this thermal scaling parameter (TSP) is shown in Eq. (3).

$$\text{TSP} = \frac{t_1 + t_2}{L_p/U_p}$$

where $L_p$ is the distance a particle travels while immersed in the surrounding gases traveling at velocity $U_p$. A particle with a TSP $<1$ solidifies prior to reaching the turbine while a particle with a TSP $>1$ is in molten form as it encounters the turbine.
effectiveness tests. For all experiments in the current study, wax was deposited on the test section surfaces. Following the deposition simulation, a thin coat of flat black paint was applied to the wax-covered surface to ensure uniform surface emissivity with a value close to 1. The IR data were then calibrated as described in the previous section to account for any changes in emissivity caused by the deposition. After paint application, an adiabatic effectiveness test was conducted to determine the effects of the existing deposition on cooling.

To simulate deposition, microcrystalline wax with a melting temperature of 351 K was used to simulate deposition. It was necessary to simulate deposition using a high melting point wax to prevent the deposits from melting because of the 328 K mainstream temperature needed to achieve maximum temperature difference between the mainstream and coolant during the adiabatic effectiveness tests. For all experiments in the current study, wax was injected during steady state at either a mainstream temperature of 295 K to achieve a TSPmax=0.3 or a mainstream temperature of 337 K to achieve a TSPmax=1.2. It is important to note that wax was injected at a constant temperature of 364 ± 1.3 K throughout the duration of each deposition test. As previously stated, wax was injected from two nozzles with a mass flowrate of 1.9 g/s per nozzle amounting to a total wax mass flowrate of 3.8 g/s for a duration of 240 s. A wax mass flowrate of 3.8 g/s for a duration of 240 s results in a particle loading of 56 ppmw (parts per million by weight), which is experienced by 8000 h of gas turbine operation with a hot gas path particulate concentration of 0.007 ppmw. Table 2 shows the particle material properties, operating conditions, and particle scaling parameters for fly ash particles in a gas turbine compared with wax particles in the laboratory wind tunnel [18–23].

Figure 6 shows particle temperatures plotted with respect to TSP for a 10 μm fly ash particle in engine conditions and a 100 μm wax particle in laboratory conditions. Although fly ash particles and wax particles are subject to different surroundings, the TSP value can be matched to scale the particle solidification time between engine and laboratory conditions. Particle solidification times, t1 and t2, from Eqs. (1) and (2) are illustrated in Fig. 6.

Surface deposition was quantified using a two-dimensional area coverage technique similar to that used by Lawson and Thole [1]. To quantify the surface coverage, the endwall surface was photographed using a Nikon D40× 10.2 megapixel digital single lens reflex (SLR) camera with a polarizing filter. For each experiment, diffuse surface lighting was created by placing a white sheet over the test section and providing upward lighting from inside the wind tunnel. By directing the lights toward the white sheet, light could be diffusely reflected evenly to prevent glare and uniformly light the surface. After each experiment, photographs were taken through four port locations on the ceiling of the test section. The photos were then stitched together to create a composite image of the surface. The composite image was then cropped and converted to an 8 bit image in which every pixel had a gray value between 0 and 255 representing the light intensity of that pixel. The white wax that deposited on the black surface created excellent contrast and easy deposition identification. The 8 bit surface image was then converted to a binary image in which all black pixels represented deposition. Deposition area coverage could then be calculated by counting the ratio of black to white pixels for a given area of interest. IMAGEJ [24] software was utilized to perform the digital image processing described above.

Figure 7 shows a composite endwall photo taken at the vane leading edge along with its corresponding 8 bit composite image binary representation. Figure 7(d) shows a color contour in which each pixel from the 8 bit image was assigned a color based on the pixel gray value. These color surface deposition plots allowed for improved contrast for qualitative deposition analysis. It is important to note that the method described above is a two-dimensional analysis method and color contour levels do not necessarily represent deposition thickness.

### Table 2 Particle properties and scaling parameters

<table>
<thead>
<tr>
<th>Engine (fly ash)</th>
<th>Laboratory (wax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter, d_p (μm)</td>
<td>0.1–10</td>
</tr>
<tr>
<td>Particle density, ρ_p (kg/m³)</td>
<td>1.980 [18]</td>
</tr>
<tr>
<td>Specific latent heat of fusion, Δh_{fus} (J/kg)</td>
<td>650,000 [19]</td>
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<tr>
<td>Specific heat, C_p (J/kg K)</td>
<td>730 [20]</td>
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<tr>
<td>Particle solidification temperature, T_{p,i} (K)</td>
<td>1.533 [21]</td>
</tr>
<tr>
<td>Mainstream gas temperature, T_e (K)</td>
<td>1.500 [22]</td>
</tr>
<tr>
<td>Particle initial temperature, T_{p,i} (K)</td>
<td>1.593 [22]</td>
</tr>
<tr>
<td>Gas viscosity, μ (kg/m s)</td>
<td>5.55 × 10⁻⁵</td>
</tr>
<tr>
<td>Particle travel distance (combustor to turbine), L_e (m)</td>
<td>0.26</td>
</tr>
<tr>
<td>Particle velocity (mainstream velocity), U_e (m/s)</td>
<td>93 [23]</td>
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<tr>
<td>Film-cooling hole diameter, D (mm)</td>
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<td>Maximum thermal scaling parameter, TSP_max</td>
<td>1.2</td>
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<tr>
<td>Stokes number, Stk</td>
<td>0.004–40</td>
</tr>
</tbody>
</table>

Because the TSP is highly dependent on particle size, the TSP of the maximum particle size, TSPmax, is used in the current study to characterize the particle phase. By ensuring that the TSPmax is matched between different experiments, the phase of the particle upon reaching the test section can be consistent.

For each experimental condition, two tests were conducted. The first test consisted of the deposition simulation during which wax was injected at steady state conditions to simulate deposition on the test section surfaces. Following the deposition simulation, a thin coat of flat black paint was applied to the wax-covered surface to ensure uniform surface emissivity with a value close to 1. The IR data were then calibrated as described in the previous section to account for any changes in emissivity caused by the deposition. After paint application, an adiabatic effectiveness test was conducted to determine the effects of the existing deposition on cooling.

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4 Discussion of Results

For the current study, a test matrix was designed to explore the effects of film-cooling momentum flux ratio, \( TSP_{\text{max}} \), and wax spray duration on endwall deposition and adiabatic effectiveness. By increasing the wax spray duration, the total mass of wax injected in a given test was increased. Table 3 shows the test matrix for the current study. It is important to note that the upstream slot flow was 0.75% of the mainstream for every experiment conducted in this study.

Prior to simulating deposition on a film-cooled surface, a flat endwall without film-cooling holes was installed to observe the deposition that occurred because of secondary flow structures alone. Figure 8 shows the 8-bit composite photographs and corresponding surface deposition plots for the deposition tests conducted using a flat endwall with no film-cooling. As shown in Fig. 8(a), deposition that occurred with \( TSP_{\text{max}}=0.3 \) was isolated mostly to the leading edge region. When exposed to a mainstream temperature of 337 K, the \( TSP_{\text{max}}=1.2 \) particles are soft and more likely to stick, resulting in deposition that was more widespread but less dense at the leading edge than the \( TSP_{\text{max}}=0.3 \) deposition. Deposition patterns shown by both cases in Fig. 8 illustrate well where deposition collects because of secondary flow structures near the endwall. The densest deposition is collected near the stagnation point downstream of the leading edge vortex. The leading edge vortex is formed by the total pressure gradient that becomes the static pressure gradient as the boundary layer flow stagnates at the vane leading edge. The pressure gradient causes the flow to move toward the endwall at which point particles with high inertia do not follow the vortex streamlines, resulting in deposition on the endwall between the vortex and the stagnation point. Also illustrated well by the deposition is the saddle point where flow separates from the endwall upstream of the leading edge vortex.

Dense deposition can also be observed inside the trailing edge of the slot upstream of the stagnation region. Local pressures on the endwall at the exit of the slot upstream of stagnation are high, resulting in either ingestion or very low coolant velocities exiting the slot. The low coolant velocity is not enough to prevent particles from impacting the surface.

Following deposition tests on the uncooled endwall, the film-cooled endwall illustrated in Fig. 2 was installed. Prior to simulating deposition, a series of baseline (no deposition) adiabatic effectiveness tests were conducted at momentum flux ratios of I = 0.23, I = 0.95, and I = 3.6. Contours illustrating spatially resolved adiabatic effectiveness values on the film-cooled endwall are shown in Fig. 9. Recall that the coolant flow condition is characterized by the momentum flux ratio of the leading edge coolant hole immediately upstream of the stagnation point. The contours

<table>
<thead>
<tr>
<th>Test No.</th>
<th>I</th>
<th>M</th>
<th>Wax mass (g)</th>
<th>( TSP_{\text{max}} )</th>
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<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>0.3</td>
<td>Deposition simulation—slot only</td>
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<tr>
<td>2</td>
<td>-</td>
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<td>600</td>
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<td>6</td>
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<td>0.3</td>
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<td>0.23</td>
<td>0.5</td>
<td>900</td>
<td>0.3</td>
<td>Deposition simulation/adiabatic effectiveness</td>
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<td>9</td>
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<td>900</td>
<td>1.2</td>
<td>Deposition simulation/adiabatic effectiveness</td>
</tr>
<tr>
<td>13</td>
<td>3.60</td>
<td>2.0</td>
<td>900</td>
<td>1.2</td>
<td>Deposition simulation/adiabatic effectiveness</td>
</tr>
</tbody>
</table>
show that coolant from the leading edge row is pulled toward the suction side of the vane, causing increased effectiveness on the suction side of stagnation. Similar to the findings of Sundaram and Thole [25], effectiveness increases with an increase in blowing ratio. Separation reduces the effectiveness immediately downstream of the leading edge row at I=3.6; however, the leading edge vortex pulls the coolant toward the endwall near the stagnation region, resulting in increased effectiveness.

Adiabatic effectiveness was laterally averaged in the streamwise direction at different locations across the pitch of the leading edge cooling row. Figure 10 shows the baseline laterally averaged effectiveness distribution for the leading edge cooling row at the three momentum flux ratios tested. Laterally averaged effectiveness increased with an increase in momentum flux ratio with a large jump in effectiveness between I=0.95 and I=3.6.

4.1 Effects of Deposition Evolution. Prior to testing the effects of mainstream temperature and momentum flux ratio, the effect of differing wax spray durations was explored to determine the effects of deposition evolution on cooling effectiveness. Three separate tests were conducted with three wax spray durations at I=0.23. Figure 11 shows the effectiveness contours and surface deposition plots for the case with no deposition along with the cases after the injection of 300 g, 600 g, and 900 g of wax. Similar to the cases with no film-cooling, deposition was densest at the stagnation region of the vane and inside the trailing edge of the upstream slot. As expected, surface deposition increased with an increase in wax injection with a larger difference between 300 g and 600 g than between 600 g and 900 g. Comparing directly between effectiveness contours and deposition plots, it is evident that the regions with the highest effectiveness (i.e., coldest surface temperatures) had the least deposition. Ai et al. [9] found that deposition capture efficiency decreased with an increase in blowing ratio and Lawson and Thole [1] observed a decrease in coolant wake deposition with an increase in momentum flux ratio. Bons et al. [5] observed trough patterns caused by the lack of deposition in cooling hole wakes on actual turbine hardware. The lack of deposition in the wakes of coolant holes on the suction side of the vane leading edge in this case is most likely because of high coolant jet velocities, preventing surface impaction of particles.

Not only did the coolant holes have an effect on deposition but deposition had an effect on the cooling effectiveness of the leading edge row. The laterally averaged effectiveness plots in Fig. 12 show that an increase in deposition causes a decrease in effectiveness everywhere along the leading edge cooling row. Deposition has a greater effect on the cooling effectiveness on the suction side of stagnation than on the pressure side. It is interesting to note that laterally averaged effectiveness values for the 600 g and 900 g cases are practically the same, indicating that effectiveness
approaches an equilibrium state between 600 g and 900 g of injection. Lawson and Thole [1] also observed that effectiveness reached an equilibrium state with an increase in deposition for a simple flat plate film-cooling study. As deposition approaches an equilibrium state, the rate at which particles deposit approaches the rate at which particles are eroded from the surface.

Area-averaged effectiveness values were calculated for the region illustrated by the white box in Fig. 11(a). Figure 13 shows the leading edge area-averaged effectiveness and effectiveness reduction relative to the baseline plotted with respect to deposition area coverage for the three wax spray duration tests. Figure 13 shows that after 300 g of wax injection the leading edge cooling effectiveness is reduced by 10%. After 600 g, effectiveness is reduced by 25% and after 900 g, effectiveness reduction reaches 26%. The difference in effectiveness reduction between 600 g and 900 g of wax injection is only 1%, which is well within the experimental uncertainty, indicating that the effect of deposition on cooling effectiveness is approaching an equilibrium state as it did in Lawson and Thole [1].

The spray duration tests presented in Figs. 11–13 revealed that 900 g of wax injection was adequate to capture the effects of deposition on cooling effectiveness. For the remainder of the tests conducted for the current study, a spray duration of 4 min was used to explore the effects of momentum flux ratio and mainstream temperature on cooling effectiveness.

4.2 Effects of Momentum Flux Ratio. As the momentum of the jet exceeds the momentum of the mainstream fluid, the jet becomes more likely to separate from the surface. Figures 14–16 show adiabatic effectiveness contour plots and surface deposition plots for \( I = 0.23 \), \( I = 0.95 \), and \( I = 3.6 \), respectively. The leading edge coolant jets are likely separated at \( I = 3.6 \); therefore, there are vast differences between the deposition pattern observed at \( I = 3.6 \) compared with the two lower momentum flux ratios. At \( I = 3.6 \) deposition is widespread downstream of the leading edge cooling holes on the pressure side of stagnation. It is clear that deposition collects everywhere outside of the coolant jet wakes, as seen in Figs. 16(a) and 16(b). At \( I = 3.6 \) deposition is very dense between cooling holes especially near the leading edge of the cooling holes. Mounds of deposition developed between the leading edge coolant holes at \( I = 3.6 \), implying that there was a blockage effect that created a recirculation region.

Sundaram and Thole [26] made laser Doppler velocimetry measurements at the stagnation point for the same cooling geometry tested in the current study. The location of the flowfield measurement plane illustrated in Fig. 17 is shown by the white line in Fig. 16(a). The flowfield in Fig. 17 shows the recirculation regions upstream and downstream of the coolant holes at \( M = 2.5 \). The recirculation regions correspond with deposition collection in the surface deposition plots shown in Fig. 16. Deposition is also collected downstream of the passage cooling holes most likely because jet separation created a recirculation region immediately downstream of these cooling holes.

It is apparent from Figs. 14–16 that deposition has a negative impact on cooling at all three momentum flux ratios tested. Figure 18 shows the area-averaged effectiveness of the leading edge cooling row for the baseline case along with the \( T_{SP,max} = 0.3 \) and \( T_{SP,max} = 1.2 \) cases. For validation purposes, Fig. 18 also shows
the area-averaged effectiveness of the same leading edge cooling row geometry tested by Sundaram and Thole [25]. The results in Fig. 18 show that leading edge effectiveness increased with an increase in momentum flux ratio with and without surface deposition. Deposition caused a noticeable reduction in area-averaged effectiveness of the leading edge cooling row at all three momentum flux ratios.

4.3 Effects of Thermal Scaling Parameter. For the cases illustrated in Figs. 14–16, the results are similar to those with no cooling in that deposition at TSP\(_{\text{max}}\) = 1.2 appears less dense at the stagnation region but more widespread than deposition at TSP\(_{\text{max}}\) = 0.3. Recall that TSP was varied by changing the mainstream air temperature. Effectiveness contours show that deposition at TSP\(_{\text{max}}\) = 1.2 has a more negative impact on cooling than deposition at TSP\(_{\text{max}}\) = 0.3. Deposition at TSP\(_{\text{max}}\) = 1.2 is collected densely around cooling holes near stagnation and appeared to partially block some cooling holes. This blocking effect is the explanation for the increased reduction in effectiveness observed at TSP\(_{\text{max}}\) = 1.2. Particles with TSP\(_{\text{max}}\) = 1.2 have higher temperatures than particles with TSP\(_{\text{max}}\) = 0.3. Particles with higher temperatures are softer and stickier, allowing them to deposit more readily upon impaction in the vicinity of cooling holes. Deposition at TSP\(_{\text{max}}\) = 1.2 is less dense near stagnation than deposition at TSP\(_{\text{max}}\) = 0.3 because the sticky particles entrained in the leading edge vortex at TSP\(_{\text{max}}\) = 1.2 are likely to deposit on the vane surface before impacting the endwall. The photographs in Fig. 19 at I = 0.23 for both TSP\(_{\text{max}}\) conditions illustrate the thick deposition on the vane surface at TSP\(_{\text{max}}\) = 1.2.

Area-averaged effectiveness was calculated for the passage row in addition to the leading edge row. The region used for taking the passage row area-average was 11D\(_2\) and is indicated by the black box in Fig. 11(a). Figure 20 shows the area-averaged effectiveness reduction relative to the baseline case for the passage and leading edge rows at TSP\(_{\text{max}}\) = 0.3 and TSP\(_{\text{max}}\) = 1.2 plotted with respect to momentum flux ratio. The results show that leading edge effectiveness reduction decreases with an increase in momentum flux ratio while passage row effectiveness reduction increases with an increase in momentum flux ratio.

In addition to the different effect of momentum flux ratio between leading edge and passage cooling rows, the effect of TSP\(_{\text{max}}\) is much greater on the passage row than on the leading edge row. Passage row effectiveness reduction reaches 32% at TSP\(_{\text{max}}\) = 1.2 and only as high as 25% at TSP\(_{\text{max}}\) = 0.3. The difference in effects observed between the passage row and the leading edge row is most likely because the leading edge coolant is less susceptible to separation because of the presence of the leading edge vortex. The leading edge vortex holds the coolant on the
endwall, which allows for increased effectiveness and reduces downstream deposition buildup. The passage row coolant, on the other hand, is more susceptible to separation, which leads to deposition accumulation close to the trailing edges of coolant holes decreasing effectiveness. The extent of deposition downstream of the coolant holes on the passage side is dependent on the TSP\textsubscript{max} value. The soft sticky particles that exist at TSP\textsubscript{max} = 1.2 lead to dense deposition downstream of passage row cooling holes ultimately leading to increased effectiveness reduction.

5 Conclusions

A method was developed to dynamically simulate solid and molten particle deposition using wax in a large scale turbine vane cascade. The effects of wax spray duration, momentum flux ratio, and mainstream temperature on endwall film-cooling effectiveness were quantified. A thermal scaling parameter was developed to characterize the phase of particles immersed in the mainstream gas path. The thermal scaling parameter was used to scale the phase of the particles from engine to laboratory conditions.

At the lowest momentum flux ratio, three tests were conducted with different wax spray durations to observe deposition development and measure the effects of deposition evolution on cooling. Little change in effectiveness and surface area coverage between 600 g and 900 g of wax injection indicated that deposition approached an equilibrium state.

Areas of dense deposition were observed at the stagnation region of the vane, downstream of the passage cooling rows, and upstream of leading edge cooling rows at high momentum flux ratios. Based on these observations compared with laser Doppler velocimetry measurements from a previous study [26], dense deposition most likely collects in areas where high vorticity causes particle impaction on the endwall.

Area-averaged effectiveness values were calculated for the leading edge and passage cooling rows. Results showed that leading edge cooling row effectiveness reduction was comparable for both low and high thermal scaling parameter values and decreased with an increase in momentum flux ratio. On the other hand, the passage cooling row experienced an increase in effectiveness reduction with an increase in momentum flux ratio. The difference in effectiveness dependence on deposition between leading edge and passage cooling rows was because jet separation at the leading edge cooling row was suppressed at high momentum flux ratios by the leading edge vortex. The buildup of deposition downstream of passage cooling holes led to a greater decrease in effectiveness with the high thermal scaling parameter than with the low thermal scaling parameter.

This study has shown that endwall cooling is highly sensitive to deposition. Excess deposition could lead to reduced cooling effectiveness and possibly turbine component failure. It is essential to understand the driving mechanisms behind deposition so that advanced film-cooling configurations can be designed to mitigate deposition.

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Nomenclature

\begin{itemize}
  \item \textit{a} = speed of sound
  \item \textit{A} = surface area
  \item \textit{C} = chord length
  \item \textit{C_p} = particle specific heat
  \item \textit{\Delta h_{\text{fus}}} = specific latent heat of fusion
  \item \textit{D} = film-cooling hole diameter, \textit{D}=0.46 cm
  \item \textit{d_p} = particle diameter
  \item \textit{\dot{h}} = heat transfer coefficient
  \item \textit{I} = momentum flux ratio, \textit{I}=\rho_a U_a^2 / \rho_s U_s^2
  \item \textit{L} = film-cooling hole length
  \item \textit{L_c} = characteristic length for Stokes number
  \item \textit{L_p} = particle travel distance
  \item \textit{M} = film-cooling blowing ratio, \textit{M}=\rho_a U_a / \rho_s U_s
  \item \textit{M_{\text{ideal}}} = blowing ratio of a loss free hole, \textit{M}_{\text{ideal}}=\sqrt{\rho_a / \rho_s} \sqrt{p_{o,c} - p_c / p_{o,s} - p_s}
  \item \textit{Ma} = Mach number, \textit{Ma}=U_a / a
  \item \textit{p} = static pressure
  \item \textit{P} = vane cascade pitch
  \item \textit{P_o} = total pressure
  \item \textit{Q} = heat loss to surroundings
  \item \textit{Re} = Reynolds number, \textit{Re}=\rho U_a C / \mu
  \item \textit{S} = nozzle guide vane span
\end{itemize}
\[
\begin{align*}
S_{T_h} &= \text{Stokes number, } S_{T_h} = \frac{\rho_p d_p^2 U_p}{18\mu L_c} \\
T &= \text{temperature} \\
T_u &= \text{turbulence intensity percent, } T_u = u'_{rms}/U \\
U &= \text{velocity} \\
V &= \text{volume} \\
X, Y, Z &= \text{local coordinates}
\end{align*}
\]

Greek
\[
\begin{align*}
\eta &= \text{adiabatic effectiveness, } \eta = (T_{aw} - T_{aw})/(T_{aw} - T_{c}) \\
\eta_l &= \text{laterally averaged effectiveness} \\
\eta_a &= \text{area-averaged effectiveness} \\
\eta_{a0} &= \text{baseline area-averaged effectiveness (no deposition)} \\
\rho &= \text{density} \\
\mu &= \text{gas dynamic viscosity}
\end{align*}
\]

Subscripts
\[
\begin{align*}
aw &= \text{adiabatic wall} \\
c &= \text{cooler} \\
ex &= \text{exit} \\
i &= \text{initial} \\
in &= \text{inlet} \\
p &= \text{particle} \\
s &= \text{solidification} \\
\infty &= \text{mainstream}
\end{align*}
\]

References


