FINAL REPORT

Experimental Investigation of Turbine Vane Heat Transfer for Alternative Fuels

DOE EPSCoR Lab Partnership Program

In collaboration with the DOE National Energy Technology Laboratory (NETL)

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Submitted by Principal Investigator

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DOE EPSCoR Program Office

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Abstract

The focus of this program was to experimentally investigate advanced gas turbine cooling schemes and the effects of and factors that contribute to surface deposition from particulate matter found in coal syngas exhaust flows on turbine airfoil heat transfer and film cooling, as well as to characterize surface roughness and determine the effects of surface deposition on turbine components. The program was a comprehensive, multi-disciplinary collaborative effort between aero-thermal and materials faculty researchers and the Department of Energy, National Energy Technology Laboratory (NETL). The primary technical objectives of the program were to evaluate the effects of combustion of syngas fuels on heat transfer to turbine vanes and blades in land-based power generation gas turbine engines. The primary questions to be answered by this investigation were:

- What are the factors that contribute to particulate deposition on film cooled gas turbine components? An experimental program was performed in a high-temperature and pressure combustion rig at the DOE NETL.
- What is the effect of coal syngas combustion and surface deposition on turbine airfoil film cooling? Deposition of particulate matter from the combustion gases can block film cooling holes, decreasing the flow of the film coolant and the film cooling effectiveness.
- How does surface deposition from coal syngas combustion affect turbine surface roughness? Increased surface roughness can increase aerodynamic losses and result in decreased turbine hot section efficiency, increasing engine fuel consumption to maintain desired power output. Convective heat transfer is also greatly affected by the surface roughness of the airfoil surface.
- Is there any significant effect of surface deposition or erosion on integrity of turbine airfoil thermal barrier coatings (TBC) and do surface deposits react with the TBC in any way to decrease its thermal insulating capability? Spallation and erosion of TBC is a persistent problem in modern turbine engines.
- What advancements in film cooling hole geometry and design can increase effectiveness of film cooling in turbines burning high-hydrogen coal syngas due to the higher heat loads and mass flow rates of the core flow? Experimental and numerical investigations of advanced cooling geometries that can improve resistance to surface deposition were performed.

The answers to these questions were investigated through experimental measurements of turbine blade surface temperature and coolant coverage (via infrared camera images and thermocouples) and time-varying surface roughness in the NETL high-pressure combustion rig with accelerated, simulated surface deposition and advanced cooling hole concepts, coupled with detailed materials analysis and characterization using conventional methods of Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), X-Ray Diffraction (XRD), 3-D Surface Topography (using a 3-D stylus profilometer). Detailed surface temperatures and cooling effectiveness could not be measured due to issues with the NETL infrared camera system. In collaboration with faculty startup funding from the principal investigator, experimental and numerical investigations were performed of an advanced film cooling hole geometry, the anti-vortex hole (AVH), focusing on improving cooling effectiveness and decreasing the counter-rotating vortex of conventional cooling holes which can entrain mainstream particulate matter to the surface. The potential benefit of this program is in gaining a fundamental understanding of how the use of alternative fuels will effect the operation of modern gas turbine engines, providing valuable data for more effective cooling designs for future turbine systems utilizing alternative fuels.

List of Accomplishments

For the final report of the program, the primary accomplishments are as shown below. Following the accomplishments is a report on the details of the various aspects of the study.

Graduate/Undergraduate Students:

1. DOE University Turbine Systems Research (UTSR) Fellowship for three (3) MS Students
2. Oak Ridge Institute for Science and Education (ORISE) Fellowship for MS Student
3. Four (4) MS thesis graduates supported either partially or in full (Murphy, Repko, Hayes, Luo) and one (1) unfunded student
4. Students published four (4) Conference papers and two (2) Journal papers. Three additional Journal papers are in preparation and another paper is under revision. Details included later in this report.
5. Two (2) undergraduate students completed their Senior Honors thesis on work performed building and benchmarking the experimental film cooling facility, and four (4) additional students worked as undergraduate researchers.

Particulate Deposition Research:

6. Processing of the coal flyash and particle sizing for particulate injection into combustion facility
7. Design of injection system for particle seeder. Procurement of Dantec PS-20 high-pressure particle seeding system
8. Atmospheric and high-pressure testing of the high-pressure seeding system. Seeding system successfully implemented in high-temperature, high-pressure combustion facility
9. Design of test coupons and procurement of base material. Fabrication of film cooled test articles.
10. Advanced TBC coating system application on film cooled test articles. Coating system architecture is $\gamma-\gamma'$ Platinum aluminide (PtAl) bond coat and 7% Yttria-stabilized Zirconia (7YSZ) top coat
11. Established Non-Disclosure Agreement with GE to match dimensionless parameters for test coupons
12. Matching of laboratory and engine conditions for particles in flow using particulate loading and Stokes similarity
13. Simulation of flyash deposition on the pressure side of a NGV with straight, inclined hole film cooling with TBC coatings and shallow trench
14. Observation of deposition rates and patterns with infrared camera system, and measurement of surface roughness at intervals during testing. Temperature measurements performed but errors in camera system prevent analysis of cooling effectiveness

Materials Analysis Research:

15. Measurement of modulus of elasticity of selected areas of the TBC system with varying deposition quantity
16. Examination of the microstructural degradation of TBC using from flyash deposition using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS)

Advanced Cooling Geometry (anti-vortex hole – AVH) Research:

Experimental Research -

17. Design of a low speed, low temperature experimental wind tunnel laboratory to non-dimensionally simulate the aerothermal environment experienced by the components in the first stage turbine in a gas turbine engine
18. Design of turbulence grids to allow turbulence intensities of 1% (no grid), 6%, and 12%
19. Design of coolant loop capable of varying cooling blowing ratios
20. Fabrication of test section surface and cylindrical straight hole and anti-vortex hole (AVH) test articles

21. Installation of thermocouples and a FLIR camera to acquire surface temperature
22. Benchmarking of facility with conventional inclined, straight cooling hole geometry
23. Transient measurement of the film cooling effectiveness and heat transfer coefficient from the different test article geometries at different turbulence levels and blowing ratios

Numerical Research -

24. Development of the numerical setup of wind tunnel for computational fluid dynamics (CFD) analysis
25. Creation of a multi-block structured computational grid for steady cases and a trimmed hexahedral mesh for unsteady cases
26. Creation of turbulence cases with 3 different turbulence intensities (5%, 10%, and 20%) and turbulent length scales (1, 3, 6)
27. CFD analysis of centerline and span-averaged adiabatic effectiveness of varying turbulence intensities and lengths scales
28. Analysis of contour plots of adiabatic effectiveness to visualize the physics of the flow for a given set of conditions and geometry.

Details of Results

The results of the research program are categorized into two distinct areas: 1) analysis of the effects of and factors that influence particulate deposition on simulated turbine airfoils with film cooling, including the effects of deposition on turbine thermal barrier coatings (TBC) and 2) experimental and numerical investigation of an advanced film-cooling hole geometry to resist particulate deposition, the anti-vortex hole (AVH). These two aspects of the research effort were performed in parallel.

In order to investigate the effects of particulate deposition, this aspect of the research effort involved simulating coal particulate deposition on the pressure side of a NGV with straight, inclined hole film cooling with TBC coatings and shallow trench by injecting processed fly ash into the aerothermal combustion facility at NETL-Morgantown and depositing the particulates onto simulated film-cooled test articles with TBC. Mr. Robert G. Murphy, a graduated MS student completed a study at NETL investigating the factors that affect particulate deposition in a simulated turbine environment. Following the particulate deposition work, material analyses were performed on the post-combustion and deposition testing articles to investigate the effects of deposition on the TBC system. This work was completed by Mr. Kevin Luo, an MS Student and a University Turbine Systems Research (UTSR) Fellowship recipient. For the advanced film-cooling geometry experimental study, a low speed, low temperature experimental wind tunnel laboratory was designed by Stephen A. Hayes, an MS Student, with the help of former undergraduate students Chad Jones, Dustin Frohnapfel, Evan Ford and Daniel Whitlow. The wind tunnel is designed to non-dimensionally simulate the aerothermal environment experienced by the components in the first stage turbine in a gas turbine engine. Measurement of the transient film cooling effectiveness and heat transfer coefficients from the different test article geometries, including the AVH, was performed at different turbulence levels and blowing ratios by graduate student Stephen Hayes with the assistance of Joshua Everett, Daniel Whitlow and David Billups. The computational fluid dynamics (CFD) aspect of the advanced film-cooling geometry study was completed by Timothy A. Repko. Steady and unsteady Reynolds Averaged Navier Stokes (RANS) cases for the AVH were completed for the centerline and span-averaged adiabatic effectiveness at variable turbulence intensities and turbulent length scales. Documented below are details of the accomplishments listed in the previous section.

<u>Particulate Deposition Research</u>:

The use of coal synthesis gas (syngas) in an Integrated Gasification Combined Cycle (IGCC) industrial gas turbine introduces contaminants into the flow that can deposit onto components in a first stage of the turbine. The deposits can alter external cooling schemes and degrade the TBC of the components or the components themselves. The study by Murphy was performed to examine the evolution and contributing factors to the growth of deposit structures in a simulated gas turbine environment. To simulate the gas turbine engine conditions, the high-pressure/high temperature aerothermal facility at the Department of Energy's (DoE) National Energy Technology Laboratory (NETL) in Morgantown, WV. The facility was operated at a pressure of 4 atm and temperatures ranging from 1480K to 1560K.

Test article geometries with four film cooling holes non-dimensionally matched to a large-scale industrial gas turbine were created to simulate the pressure side of a first stage vane. The test articles had impaction angles of 10- and 20-degree angles to the mainstream flow and were either bare metal or had a TBC system placed on them. Isometric views of the test article designs are shown in Figure 2. The thermal barrier coatings were applied to each test article using a novel directed vapor deposition (DVD) process. Approximately 400 μm of ceramic top coat layer was applied as 7% Yttrium Stabilized Zirconia (7YSZ). A Υ-Υ' platinum aluminide (PtAl) bond coat, developed by Brian Gleeson at the University of Pittsburgh, is applied with an approximate thickness of 15-20 μm. The cooling holes were masked during the coating process, which created a shallow trench, a configuration used in modern gas turbine components. Figure 1 contains images of TBC coated 10- and 20-degree angled test articles. Figure 2 shows images of the DOE NETL test facility and test section.

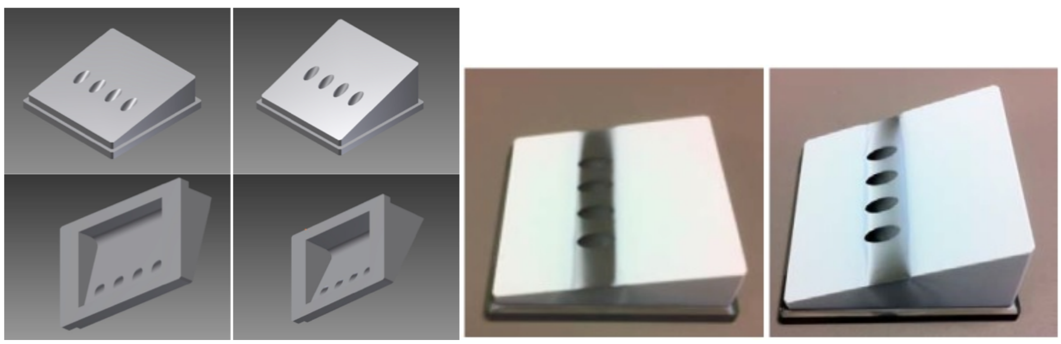


Figure 1. Images of 10° (Left) and 20° (Right) TBC coated test articles

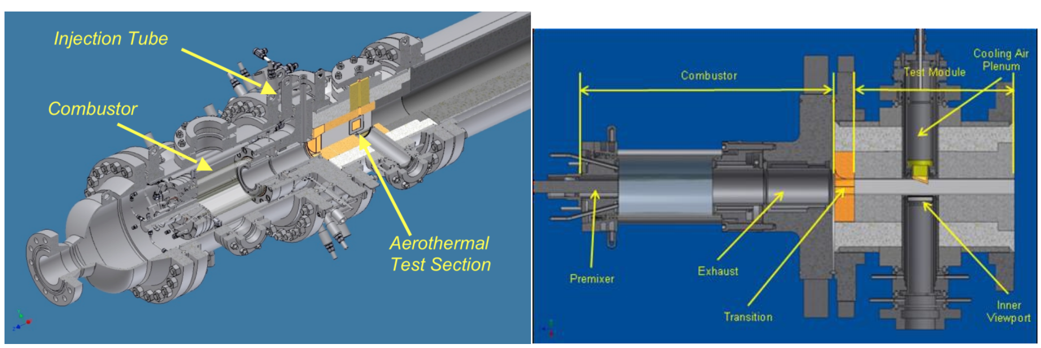


Figure 2. DOE NETL Test facility and test section

To simulate the syngas contaminants, fly ash was processed by drying, grinding, and filtering and injected into the high-pressure combustion facility. After filtration, the mean particle size of the processed fly ash was measured by a LS Particle Size Analyzer to be approximately 13 μm. Table 1 displays the composition of the bituminous fly ash in the current study. To scale the particle inertial characteristics and set the desired mean particle diameter, the Stokes number was matched between engine conditions and laboratory. The Stokes numbers were calculated for fly ash particles that range from 0.5 μm to 47 μm for the engine and laboratory conditions based on mainstream temperature, fly ash density, hole diameter, mainstream viscosity, mainstream velocity, and particle size. Lastly, fly ash particulate is injected into the high-pressure combustion rig using a PS-20 Scitek pressurized particle seeder. Particulate loading (ppmw-hr) was matched for loadings that exist in actual gas turbine engines that operate over a period of 10,000 hours. The particulate concentration (ppmw) was increased to reduce the required hours in the laboratory. The test articles are placed into the test section which is designed to allow optical access for thermal image acquisition.

Table 1. Bituminous coal ash composition

Oxides:	**SiO_2**	**CaO**	**Fe_2O_3**	**Al_2O_3**	**SO_3**	**K_2O**
wt. %	53.8	4.39	8.87	25.35	1.15	2.23

Five factors that affect the growth of deposit structures in a simulated gas turbine environment were examined: 1) freestream temperature, 2) impaction angle, 3) cooling blowing ratio, 4) coating process (bare metal vs. TBC), and 5) particulate loading. The results were observed qualitatively from time lapsed images during the high-pressure and temperature facility. Time lapsed images (approximately 20 minutes apart) showing the formation of deposition during a 3-hour operation can be seen in Figure 3. The study found the amount of deposition increased as the freestream temperature, impaction angle, and particulate loading increased. TBC coated test articles also had significantly more deposition that the bare metal counterpart. Lastly, as the cooling blowing ratio decreased, the amount of deposition increased. An observation throughout the experiment was that deposition formation only adhered onto one side of the test articles due to a large deposit structure formation on the transition piece upstream of the test section. The transition piece deposition structure caused a swirl effect which led to an uneven distribution of the flyash. Surface roughness scans of the test articles showed deposit growth as operating time increases. Additional details of results can be found in Murphy et al. [1,2]

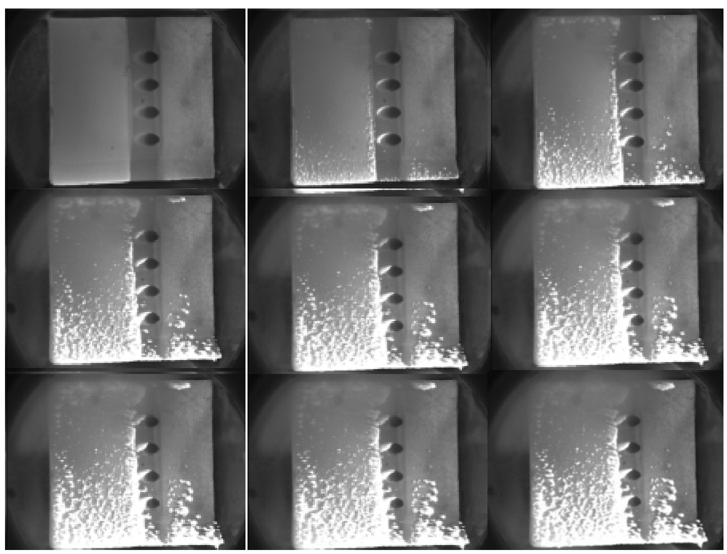
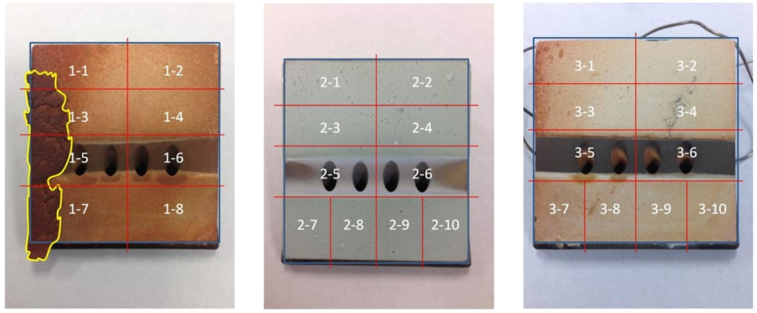


Figure 3. Time lapsed images during a 3-hour test showing formation of deposits.

Materials Analysis Research:

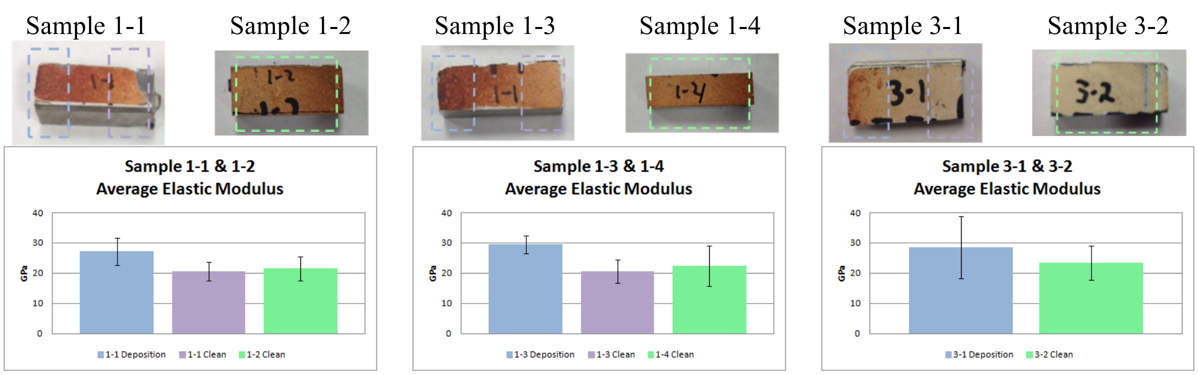
Following the experimental testing at NETL, detailed materials analyses were performed of the effects of deposition on the TBC system of the test articles. The test articles were sectioned into test samples to allow for further testing. The test sample labels prior to sectioning are shown in Figure 4. Test article 1 has an impaction angle of 20-degree and is the most heavily deposited test article. The deposition is highlighted in the leftmost image of Figure 4. Test article 2 is an unexposed test article which allowed for a normalized surface stiffness analysis. Test article 3 has an impaction angle of 10-degree and has a light amount of deposition.



Test Article 1 Test Article 2 Test Article 3

Figure 4. Test sample label for the three test articles.

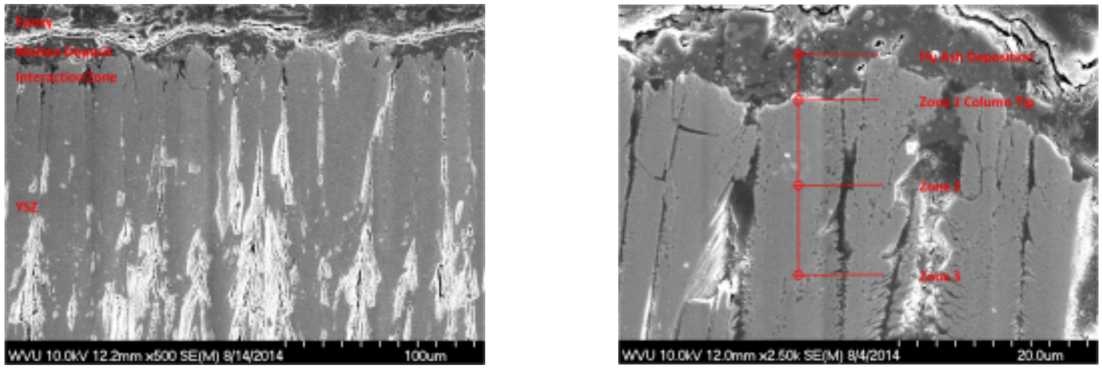
A micro-indentation method developed by Dr. Bruce S. Kang and his Ph. D student Dumbi A. Otunyo, in collaboration with DOE NETL, allowed for the modulus of elasticity to be evaluated of the test samples in areas with varying quantities of deposition. The results of the micro-indentation on test article 2 gave the unexposed Young's modulus value ($E_{unexposed}$) of 20.93 GPa. The multiple partial unloading micro-indention technique was performed on samples 1-1, 1-2, 1-3, 1-4, 3-1, and 3-2. Figure 5a contains the image and results for samples 1-1 and 1-2. The colored dashed boxes in the images of the samples correspond with the averaged elastic modulus value in the lower chart of Figure 5a. The portion of sample 1-1 encompassed by the blue dashed box contained an area where molten deposits had adhered onto the TBC prior to the sectioning. The infiltrated area exhibited a higher modulus of elasticity than those of the unexposed articles or areas along the same sample or same plane without any deposition adherence. The same increase in Young's modulus can be observed for samples 1-3 and 1-4 (Figure 5b) and samples 3-1 and 3-2 (Figure 5c). The elastic modulus for sample 3-1 was recorded for the area with deposition only due to sample compliance issues. The results found that the modulus of elasticity increased in areas where deposition had adhered onto the DVD YSZ coating. The increase in surface stiffness leads to the reduction in strain tolerance of the ceramic top coat. The loss of strain tolerance promotes the tendency for the TBC to delaminate and will result in spallation and loss of coating protection.



(a) (b) (c)

Figure 5. Image of test samples and their values for averaged TBC modulus of elasticity for a) sample 1-1 and 1-2, b) sample 1-3 and 1-4, and c) sample 3-1 and 3-2.

After the evaluation on the mechanical properties, the samples were mounted and polished for SEM and EDS analyses. Microstructural characterization was performed using SEM for micrographs of the samples and EDS for spectrum analysis and elemental mapping of the infiltration of the deposits into the YSZ coating. The SEM micrographs showed a higher tendency of delamination of the YSZ coatings in areas where deposition is abundant. In addition, a dissolution-reprecipitation mechanism is found in the YSZ columnar tips/deposition interaction zone. The ceramic coating material dissolves within the molten deposits and reprecipitates in one of the modified crystalline phases of the YSZ. The EDS mapping was showed the shallow infiltration depth of the molten flyash deposition (~10-20 μm). Even though the deposition did not penetrate deeply, yttria migration from the YSZ into the deposition can still be confirmed using the chemical composition spectrum analysis, Figure 6 and Table 2. Additional details of results can be found in Luo et al. [3,4]



(a) (b)

Figure 6. Cross-section views of a) TBC on sample 1-3 with molten deposits, their region description, and b) locations of EDS spectrum analysis

Table 2. Chemical composition (excluding oxygen) of the flyash deposition and zones 1-3 in Figure 6b.

Constituent/wt %	Si	Al	Fe	Y	Zr
Original Fly Ash	19.57	10.44	4.83	-	-
Molten deposit	23.23	12.98	5.76	1.35	9.54
1 (Column Tips)	5.77	4.44	1.83	5.24	56.87
2 (10 µm)	0.66	0.03	0.35	6.74	75.32
3 (20 µm)	0.53	0.01	0.21	7.31	77.04

<u>Advanced Cooling Geometry (anti-vortex hole – AVH) Experimental Research</u>:

The advanced film-cooling geometry study commenced with the design and construction of a low-speed, low-temperature experimental wind tunnel laboratory by MS student Stephen Hayes. An isometric view and a constructed view can been seen in Figure 7a and 7b respectively. Cylindrical hole and AVH test articles are fabricated and placed into the test section of the wind tunnel. The AVH design introduces side holes to the main cylindrical hole in an effort to reduce the vorticity from the counter-rotating vortex (CRV) pair commonly found in conventional straight inclined holes. The AVH test article is shown Figure 8. In addition, turbulence grids were fabricated to allow for three options for turbulence intensities (1%, 6%, and 12%). Surface temperature data is acquired by transient IR thermography by a FLIR A655sc camera.

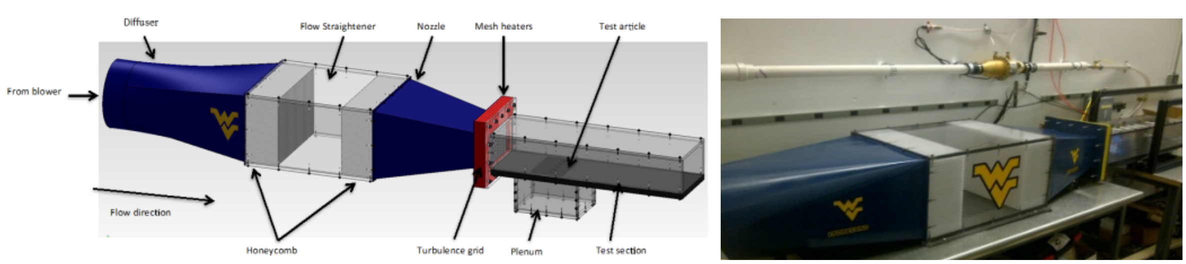


Figure 7. a) SolidWorks model of wind tunnel and b) experimental wind tunnel at WVU.

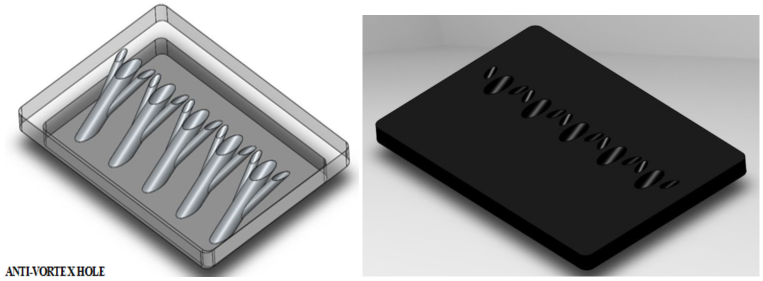


Figure 8. Isometric view of the design of the AVH test article

Following the construction of the wind tunnel, the cylindrical straight hole test article was tested to benchmark the adiabatic film cooling effectiveness (η) and heat transfer coefficient (h) trends to published literature. Once the wind tunnel was benchmarked, testing was performed on the AVH test article and the adiabatic film cooling effectiveness and heat transfer coefficient are recorded at varying turbulence levels and blowing ratios. Figure 8 shows sample data from temperature contour plots and centerline cooling effectiveness results. The results show that the cooling effectiveness increases as the turbulence intensity and blowing ratio increases. This will also result in decreased ingestion of particulate due to reduction in the counter rotating vortex pair, mitigating particulate deposition. Additional results are being published in Hayes et al. [5,6] to be submitted in Spring 2015.

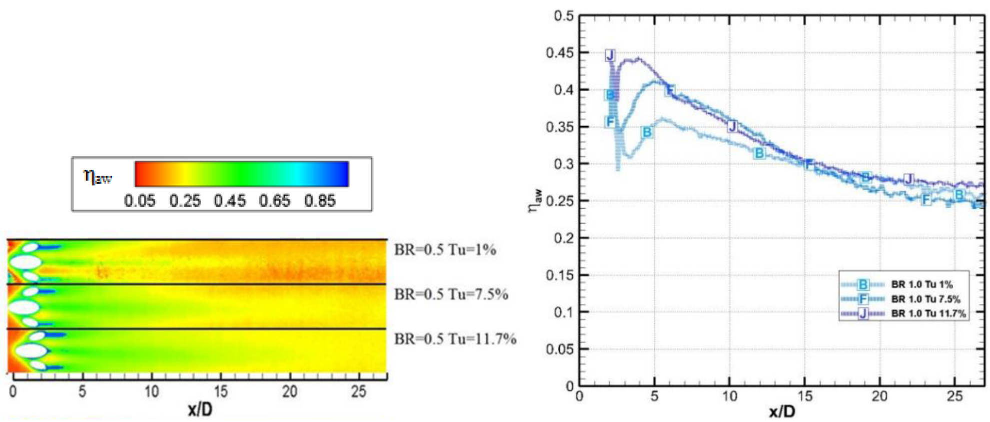


Figure 9. Experimental film cooling results with varying turbulence intensity

<u>Advanced Cooling Geometry (anti-vortex hole – AVH) Numerical Research</u>:

In parallel with the experiments, a numerical investigation of the AVH geometry at elevated turbulence levels was completed. A portion of the wind tunnel is used for the control volume of the CFD. Within the control volume, the grid is created based on steady cases (multi-block structured computational grid) and unsteady cases (trimmed hexahedral mesh). The grid and set of the computational domain of the control volume is shown in Figure 10. Three different turbulence intensities (5%, 10%, and 20%) and 3 different turbulent length scales, Λ_x/d_m, (1, 3, and 6) are used in the numerical study. The turbulence cases are simulated with either an adiabatic condition at the wall or a specified heat flux at the wall. The 3 unsteady cases were examined at a constant length scale.

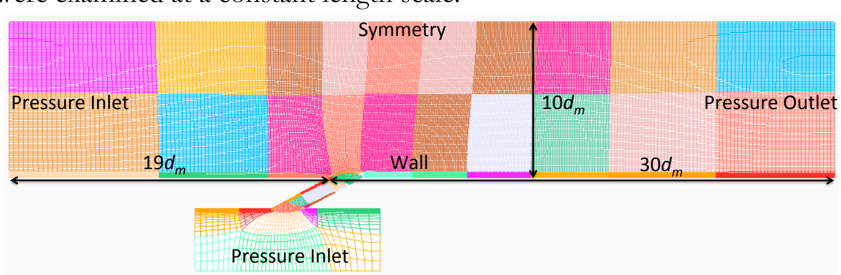


Figure 10. CV Grid and Setup of Computational Domain

Contour plots of numerical results with varying turbulence intensity for both RANS and URANS are shown in Figure 11. The results show at low turbulence cases, the lateral spreading of the coolant is not as pronounce as in the higher levels of turbulence, which show an increase in lateral spreading. The results found that at a high blowing ratio and density ratio, higher freestream turbulence levels increase the film cooling effectiveness of the AVH geometry tested. This compares favorably with the experimental results shown in Figure 9. Adiabatic film effectiveness data was presented showing improvements in cooling with increasing turbulence intensity and length scale. The length scale was shown to have little to no effect at the low turbulence level and a small but noticeable effect at high turbulence intensity. The trends for the film cooling effectiveness were matched with steady and unsteady RANS models although magnitudes were slightly different. Lastly a heat transfer analysis was presented to show that there is a net benefit through the use of the AVH concept. Further details can be found in Repko et al. [7] and in additional papers to be published by Repko et al. [8,9], which are currently under revision, or in preparation.

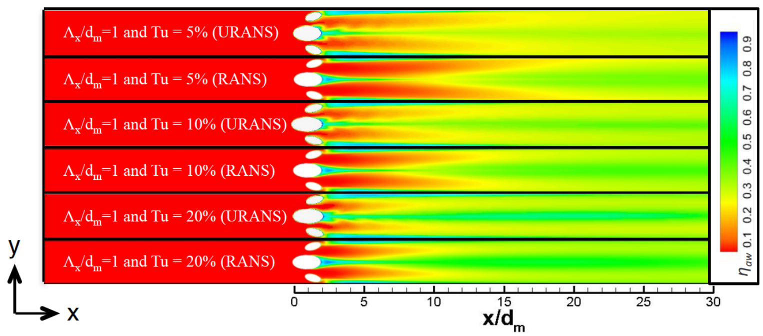


Figure 11. Numerical film cooling results with varying turbulence intensity

Publications/References

Note some papers below are not referenced in the results section of the report. Papers are organized according to category, and are therefore not in the order they appear in the report text.

Conference Papers:

Hunley, B.K., Nix, A.C. and Heidmann, J.D., 2010, "A Preliminary Study on the Effect of High Freestream Turbulence on Anti-Vortex Film Cooling Design at High Blowing Ratio," ASME GT2010-22077

[1] Murphy, R.G., Nix, A.C., Lawson, S.A. and Straub, D., 2012, "Preliminary Experimental Investigation of the Effects of Particulate Deposition on Turbine Film-Cooling in a High-pressure Combustion Facility," ASME GT2012-68806

[2] Murphy, R.G, Nix, A. C., Lawson, S. A., Straub, D. and Beer, S. K., 2013, "Investigation of Factors that Contribute to Deposition Formation on Turbine Components in a High-Pressure Combustion Facility," GT2013-94657

[7] Repko, T. W., Nix, A. C. and Heidmann, J.D., 2013, "A Parametric Numerical Study of the Effects of Freestream Turbulence Intensity and Length Scale on Anti-Vortex Film Cooling Design at High Blowing Ratio," HT2013-17255

Journal Papers:

[3] Luo, K., Nix, A.C., Kang, B.S. and Otunyo, D.A., 2014, "Effects of Syngas Particulate Fly Ash Deposition on the Mechanical Properties of Thermal Barrier Coatings on Simulated Film-Cooled Turbine Vane Components," *Int. Journal of Clean Coal and Energy, 3, 54-64*.

[4] Luo, K., Nix, A.C., and Sabolsky, E.M., 2015, "Microstructural Degradation of Thermal Barrier coatings on an Integrated Gasification Combined Cycle (IGCC) Simulated Film-Cooled Turbine Vane Pressure Surface Due to Particulate Fly Ash Deposition," *Int. Journal of Clean Coal and Energy, 4, 1-10.*

[8] Repko, T. W., Nix, A. C. and Heidmann, J.D., 2014, "A Parametric Numerical Study of the Effects of Freestream Turbulence Intensity and Length Scale on Anti-Vortex Film Cooling Design at High Blowing Ratio," submitted to *ASME Journal of Heat Transfer* – Under Revision

Journal papers in Preparation:

[5] Hayes, S.A. and Nix, A.C., 2015 "Development of a Low Speed, Low Temperature Facility for Film Cooling Analysis," in preparation to be submitted to *Journal of Energy and Power Engineering*

[6] Hayes, S.A., Nix, A.C. and Billups, D.T., 2015 "Experimental Investigation of Freestream Turbulence on an Anti-vortex Hole," in preparation to be submitted to *Journal of Energy and Power Engineering*

[9] Repko, T. W. and Nix, A. C., 2014 "Flow Visualization of Multi-Hole Film-Cooling Flow," in preparation to be submitted to *Journal of Flow Control, Measurement and Visualization*

Personnel

From the years 2009 to 2014, the program has supported the PI, Dr. Andrew Nix, a post-doctoral student and several graduate and undergraduate students. Detailed below are the personnel supported by this project.

- Post-Doctoral Researcher - Seth Lawson, completed work on the effects of simulated particulate deposition on the film cooling on a gas turbine first stage vane. He was supported part time for approximately six months. Lawson is currently employed full-time by DOE NETL in Morgantown, WV.
- MS Graduate Student - Robert Murphy, worked on the high-pressure and temperature combustion facilty deposition research. Murphy was a recipient of the ORISE Fellowship at NETL and the DOE UTSR Fellowship at Solar Turbines. He was supported full-time for 3 years of the program. He is currently employed by Solar Turbines in San Diego, CA.
- MS Graduate Student - Timothy Repko, worked on CFD of the AVH geometry. He was supported part-time on this program (approximately 1 month) with the remainder of support by internal funding. He received a DOE UTSR Fellowship at Solar Turbines. He is currently employed at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD.
- MS Graduate Student - Stephen Hayes, designed and fabricated the WVU turbine cooling wind tunnel and completed the experimental study of the AVH geometry at varying turbulence intensities and blowing ratio. He was supported full time by internal funding. He is currently employed by HurleyIR Thermography in Mt. Airy, MD.
- MS Graduate Student – Kevin Luo, was responsible for the materials analysis portion of the work. He was supported full time by internal funding. He received a DOE UTSR Fellowship at GE Power and water and is currently employed there full time.
- Undergraduate Students – undergraduate student researchers worked on the program, but were supported primarily from internal funding and some undergraduate research grants from Pratt and Whitney Canada in Bridegport, WV. Students supported were Dustin Frohnapfel (Senior Honors thesis), Evan Ford (Senior Honors thesis), Chad Jones, Daniel Whitlow, Josh Everett and David Billups. Mr. Jones and Mr. Frohnapfel were supported part-time for approximately 4 months of the program.
- Program Coordinator – Tom Spencer, supported for administrative management of the program. Mr. Spencer was supported part-time, approximately 10% of his time over the project period.

While not funded under this program, WVU acknowledges the help and support on this lab partnership program from Mr. Doug Straub and Dr. Randall Gemmen from the DOE NETL Office of Research and Development.

Current and Pending Support

The following proposed programs are synergistic with the current DOE EPSCoR program, with one program focusing on turbine cooling in the WVU turbine wind tunnel, and the other program focusing on particulate deposition and its effects on turbine TBCs.. Following this is the other current and pending support for the PI. These two programs are the extent of pending support by the PI at this time.

- Design, Evaluation, Optimization and Control of Cooled Turbine Rotor Tips: A Numerical and Experimental Approach

  Source of Support: DOE NETL University Turbines System Research Program

  Total Award Amount: $312,090

  Total Award Period Covered: 08-01-2015/ 07-31-2018

- Modeling the Impact of Silica Particle Ingestion and Deposition on Turbomachinery Life (WVU PI)

  Source of Support: RJ Lee Group/Air Force Research Lab

  Total Award Amount: $95,608

  Total Award Period Covered: 6/1/2015- 5/31/2017

Listed below is current support for the principal investigator. These programs are not synergistic with the work reported herein.

- Electrified Vehicle Educational Resources for Efficient and Sustainable Transportation (Everest) - WVU EcoCAR 3 (PI)

  Source of Support: Argonne National Labs

  Total Award Amount: $260,000

  Total Award Period Covered: 8/15/2014- 8/14/2018

- Assessing Fugitive Methane Emissions Impact Using Natural Gas Engines in Unconventional Resource Development (PI)

  Source of Support: DOE NETL

  Total Award Amount: $1,499,830

  Total Award Period Covered: 10/1/13-3/31/16

- Emissions Analysis of WMATA Transit Buses – FY14-FY18 (PI)

  Source of Support: Washington Metropolitan Area Transit Authority (WMATA)

  Total Award Amount: $1,037,714 ($392,269 Awarded in 2014)

  Total Award Period Covered: 5/1/14-10/1/18

- WVU-PMI R&D Support for Micro-Hydro Turbine (MHT) Systems (PI)

  Source of Support: Preston Machine Inc.

  Total Award Amount: $13,138

  Total Award Period Covered: 11/1/2013- 4/30/2015

Cost Status:

Shown in the table below is the approved budget, actual costs incurred as of the date of this report and remaining funds. WVU cost share includes tuition waivers for an MS student as well as faculty salary during the Spring and Fall semesters, exceeding the required 10% cost share by $6,521. NETL cost share was handled directly between the DOE agencies, WVU is not involved with this aspect of the budget details. However, in Year 1, DOE NETL cost share was paid to the University as a portion of the total project costs, as shown in the cost status table below.

Table 2. Cost Status

Category	Budget	2009 - 2014 Expenditures (August 15, 20109- April 14, 2014)	Balance
Personnel (Principals, students technical and clerical)	$191,323	$231,416	-$40,093
Fringe Benefits	$38,523	$50,163	-$11,640
Travel	$15,000	$25,005	$-10,005
Supplies, General Expenses, Materials Analyses and Major Equipment	$100,000	$43,458	$56,542
Overhead	$89,660	$84,464	$5,196
Total DOE Share	$434,506	$434,506	$0
NETL Year 1 Contribution	$15,000	$15,000	$0
Cost Share	$45,000	$51,521	$6,521
Total Program Cost	$494,506	$501,027	$6,521