the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Turbine Thermal Management—NETL-RUA

Background

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. With the Hydrogen Turbine Program, NETL is leading the research, development, and demonstration of technologies to achieve power production from high-hydrogen-content fuels derived from coal that is clean, efficient, and cost-effective, and minimizes carbon dioxide (CO_2) emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

The NETL Regional University Alliance (RUA) is an applied research collaboration that combines NETL's fossil energy expertise with the broad capabilities of five nationally recognized regional universities, of which three are participating in this project: Pennsylvania State University (Penn State), University of Pittsburgh, and Virginia Polytechnic Institute and State University (Virginia Tech). In addition, there are several industry collaborators, and URS is the NETL site support coordinator.

The NETL-RUA Turbine Thermal Management project supports the Hydrogen Turbine Program through conduct of novel, fundamental, basic, and applied research in the areas of aerothermal heat transfer, coatings development, and secondary flow control. This research project utilizes the extensive expertise and facilities available at NETL and the participating universities. The research approach includes exploratory studies based on scaled models and prototype coupon tests conducted under realistic high-temperature, pressurized turbine operating conditions. This project has been structured to address design, manufacturing and bench-scale performance assessment of aerothermal and materials concepts, and incorporation of these concepts into prototype airfoil configurations.

Project Description

The Turbine Thermal Management project is focused on basic and applied technology development in the areas of heat transfer, materials development, and secondary flow control. Specific objectives are as follows:

Aerothermal and Heat Transfer: Identify internal and external airfoil cooling concepts that provide composite benefit for reduced cooling flow and heat management, and which can be commercially manufactured. At least one new turbine cooling technology concept will be developed and demonstrated under realistic engine

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PARTNERS

Regional University Alliance
Coatings For Industry
Mikro Systems Inc.
Corrosion Consultants Inc.
Ames Laboratory
Pratt & Whitney
URS

PERFORMANCE PERIOD

Start Date	**End Date**
10/01/2011	09/30/2013

(annual continuations)

COST

Total Project Value
$3,240,000

DOE/Non-DOE Share
$3,240,000 / $0

AWARD NUMBER

FWP-2012.03.02

U.S. DEPARTMENT OF ENERGY

operating conditions. Concepts include NETL-RUA's near-surface embedded micro-channel concept, porous media thermal barrier coatings (TBCs), and/or tripod-hole film cooling configurations.

Coatings and Materials Development: Develop bond coat, diffusion barrier, and extreme temperature TBCs as an integrated composite-architecture for utilization in next generation land-based engines. Expand NETL-RUA's programmatic direction and focus through initiation of research on ceramic matrix composites and oxide dispersion strengthened material systems for use at temperatures exceeding 1400 °C. The performance and extended durability of these materials systems are being assessed through bench-scale isothermal and thermal cycling/flux testing.

Design Integration and Testing: Utilizing enhanced heat transfer internal and film cooling designs, commercially cast coupon test articles for heat transfer assessment at near room temperature and at high temperature under pressurized combustion gas conditions generated in NETL's aerothermal test facility in Morgantown, WV.

Secondary Flow Rotating Rig: Design and construct a world-class test facility for testing new cooling improvement strategies for the turbine rotating blade platform, and develop performance data relevant to initial concept designs and/or platform modifications. The primary focus of the turbine test facility is to increase turbine efficiencies by using disruptive new designs in sealing the interfaces between stationary and rotating airfoil components. The main driver of this effort is development of new designs that will lead to reduction in fuel usage by an order of magnitude or more. The facility will include a section of a turbine including a vane/blade/vane (i.e., 1.5-stage turbine), which will be operated at conditions replicating those in a modern gas turbine engine.

In 2014, the Turbine Thermal Management project will begin to explore pressure gain combustion and advanced supercritical CO_2 cycles as a possible means to contribute to overall improved plant operating efficiency.

Goals and Objectives

The Turbine Thermal Management project is being conducted as an NETL-RUA team effort to initially solidify new concepts and innovation, followed by scaled model testing to quantify the efficiency benefits of the conceptual innovations, and completed with technology demonstration under realistic, bench-scale, turbine operating conditions for validation. Technical expertise and facilities needed for this research are available at NETL and participating univer-sities. Major technical goals of this research effort include:

- Development of novel, manufacturable, internal airfoil cooling technology con-cepts that achieve a cooling enhancement factor of approximately five over that of smooth, internal airfoil cooling channel passages.

- Development of advanced, manufacturable airfoil film cooling concepts that achieve a 50 percent reduction in required cooling flow.

- Design, construction, and operation of a world-class t est facility for testing advanced sealing improvement strategies for the turbine rotating blade platform to ultimately reduce fuel burn.

- Development of advanced material system architectures that permit operation of turbine airfoils at temperatures at least 50–100 °C higher than current state-of-the-art components.

FY13 Accomplishments

Aerothermal and Heat Transfer:

- Detailed experimental studies were conducted at the University of Pittsburgh using detached circular pin-fin arrays arranged in a 2-D configuration to demonstrate enhanced heat transfer over smooth cooling channel surfaces. Pin-fin arrays with smaller inter-pin spacing in the span-wise direction were shown to perform as a row of jets which induce high heat transfer at the region immediately behind the pins (Figure 1). Current test data indicate comparable heat transfer enhancement to that of a typical fully-bridged circular pin-fin array.

- Detailed experimental and numerical studies were conducted on jet impingement channels with staggered and angled jets for NETL-RUA's near surface embedded micro-channel cooling concept. High heat transfer was observed at the upstream region caused by the impingement effects from the first, second and third jets. The heat transfer at the downstream region decreased substantially as the result of crossflow effects. By staggering and having inclined jets, better mixing and additional vortices result, with an 20% heat transfer enhancement in the channel.

- Numerical studies using ANSYS CFX were conducted on dimpled and hemispherical protrusion trailing edge zig-zag channel designs. Qualitative comparisons indicated that the zig-zag channels with dimples and hemisperical protrusions have lower heat transfer performance in comparison to the zig-zag channels that contain ribs. The design/configuration of zig-zag channel with dimples and hemisperical protrusions is being revised and further evaluated using ANSYS CFX to down-select the optimized geometry for further experimental testing.

- Heat transfer and pressure loss testing conducted with a triple impingement trailing edge coupon at near-room temperature indicated that with the presence of 90 ° inlet and impingement at the upstream region, the total heat transfer enhancement was 20% higher than previously considered cooling configurations.

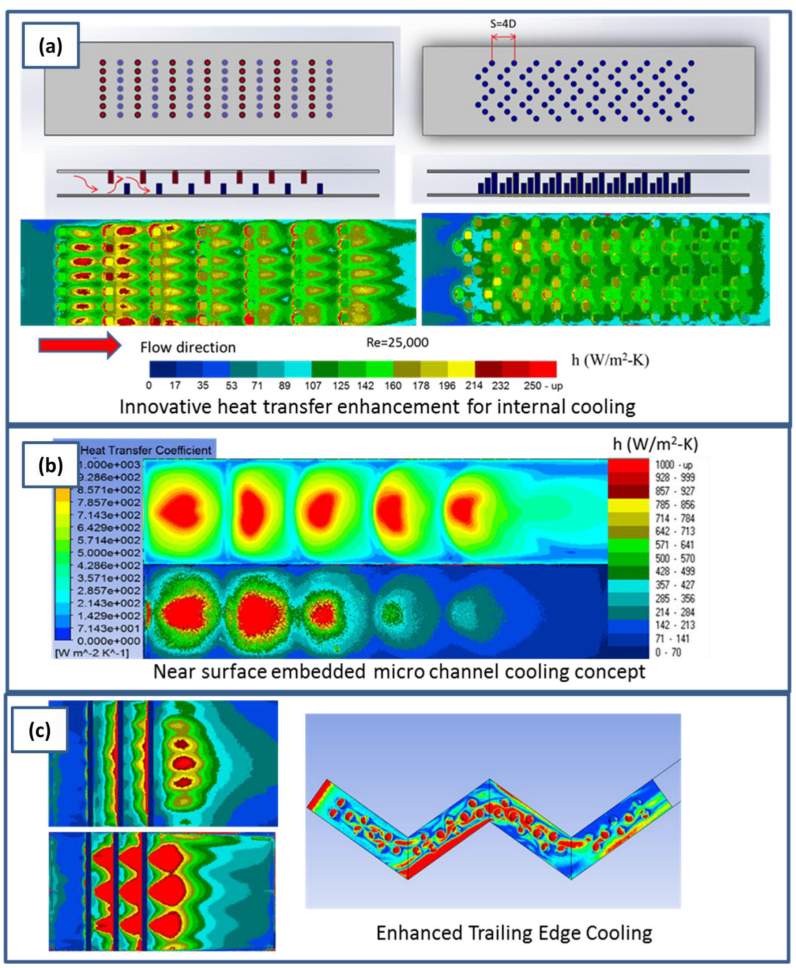

Figure 1. Results from Heat Transfer Enhancement Studies Conducted at the University of Pittsburgh for Advanced Internal Airfoil Cooling Concepts.

- The effects of blowing ratio, density ratio and hole geometry were studied at Virginia Tech to provide a clear understanding of parametric effects on tripod hole film cooling geometries. The 15 ° layback antivortex hole design was shown to be an optimal design in terms of overall performance (Figure 2). These designs were tested in a flat plate wind tunnel and on a low speed vane cascade. In all cases, the tripod hole configuration provided over 50% improvement in cooling effectiveness while using 50% less coolant mass even while operating at extremely high blowing ratios of 4.0.

- Thermal stress distribution analyses were conducted for Haynes 230 coupons containing film cooling tripod holes. Major stress concentrations within the Haynes 230 coupon were not identified, and static thermal gradients are not considered to be an issue for the tripod hole configuration. This effort is being expanded to address similar stress within CM247 tripod hole coupons which will be commercially cast and subsequently tested in NETL's high temperature, pressurized, aerothermal test facility in Morgantown, WV.

Coatings and Materials Development:

- Efforts were focused at NETL, CFI, and the University of Pittsburgh on the application of NETL-CFI's wet slurry diffusion bond coat system on CM247, MarM247, IN939, PM2000, Hayne 230, and Ni-ODS substrates. All coatings consisted of a β-NiAl matrix with distribution of (Cr, Ta, W)-rich precipitates that were dependent on the substrate alloy. Initial isothermal oxidation testing for 100 hours at 1100 ºC led to the formation of an external layer of alumina. The aluminide coating that formed from the slurry on the Fe-based PM2000 alloy from the AID coating-deposition process contained an extensive amount of Kirkendall voids, which detrimentally affected the coating integrity during subsequent thermal exposure.

- Development of a thin film ODS-layer on channeled nickel-based superalloys at Ames Laboratory was directed to production of NETL-RUA's near surface embedded micro-cooling channel effort. Ni-ODS powder composition and size fractions were analyzed with respect to oxygen content. Removal of powder particulates 25 µm greatly reduced the oxide content in the resulting coating. Selection of the appropriate deposition process was undertaken to generate dense ODS architectures. HVOF processing was selected for minimal oxidation during deposition while maintaining coating density.

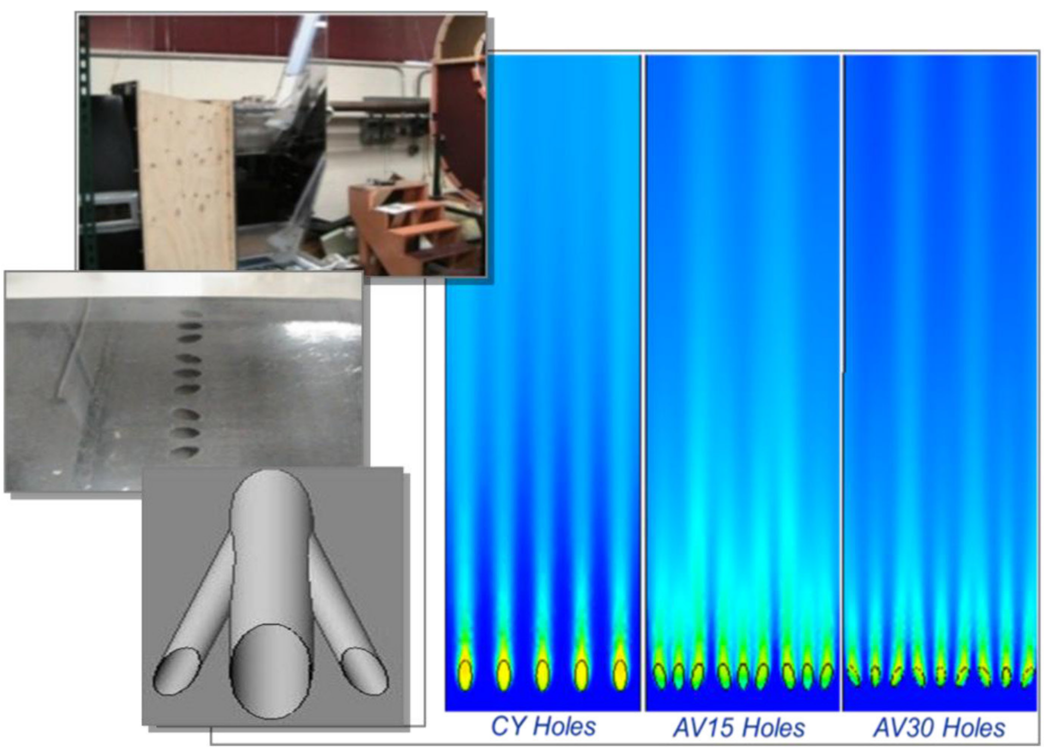

Figure 2. Virginia Tech's Tripod Hole Film Cooling Configuration, Laboratory Test Equipment and Recent Experimental Results Demonstrating Enhanced Cooling Effectiveness over Current State-of-the-Art Film Cooling Configurations.

- Efforts were also focused on determining the appropriate processing conditions for application of HVOF Ni-ODS. Reduced temperature combustion conditions were found that generated a dense coating with minimal oxidation. Liquid nitrogen substrate cooling was also effective for reducing oxidation similar to direct HIP'ing. XRD analyses of the heat-treated HVOF coupons confirmed that oxygen-exchange reaction capability of precursor Ni-ODS powders was maintained through thermal spray deposition (Figure 3).

- A thermoset matrix composite (TSMC) was selected as a viable sacrificial channel filler material for deposition of Ni-ODS on nickel-based superalloys (Figure 4). The filler material consisting of alumina was identified to be ideal for ease of manufacturing, and which withstood both the thermal and mechanical requirements of HVOF. Removal of the TSMC post Ni-ODS deposition via full decomposition was shown to occur at 500-600 °C.

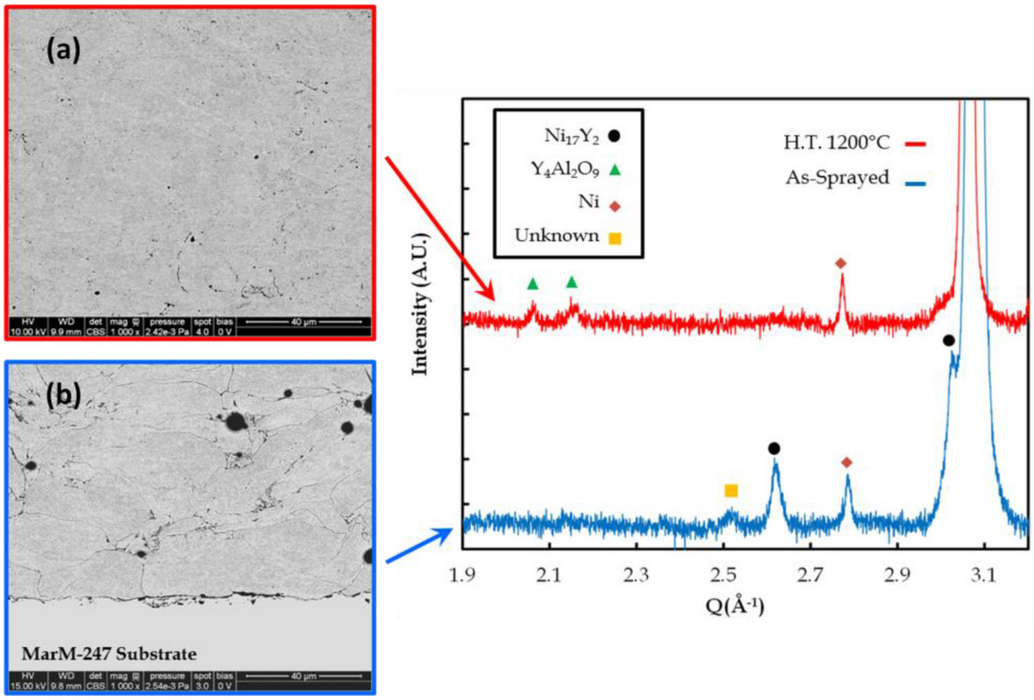

Figure 3. Microstructure of the Ames University HVOF Ni-ODS Overlay Coating on MarM-247 in the (a) Heat-Treated and (b) As-Sprayed Condition along with Corresponding X-Ray Spectra Indicating The Oxygen-Exchange Reaction and Precipitation of Oxide Dispersion Phase ($Y_4Al_2O_9$).

Figure 4. Ames Laboratory Grit Blasted Near Surface Embedded Micro-Channel Concept after Impregnation with Fugitive Thermoset Filler along the External Channels.

Design Integration and Testing:

- CM247 test coupons containing fully-bridged pin-fin internal cooling arrays, as well as zig-zag trailing edge cooling architectures were successfully cast at Mikro Systems Inc (Figure 5). Computer tomography (CT) scans of the internal configurations at NETL identified the robustness of the TOMO fabrication techniques used by Mikro Systems Inc., for production of complex parts. Similar efforts are underway for production of the first set of CM247 cast coupons containing tripod hole film cooling architectures.

- Optical pyrometer methods were developed at NETL to measure spatially resolved temperatures on test coupons within NETL's high temperature, pressurized aerothermal test facility. The accuracy of the optical measurements was determined to be within 8 °C of thermocouple readings. Additional testing was conducted to characterize incident radiation on the coupons during high temperature exposure. Spatial variation in the incident radiation was characterized which ultimately led to improvement in temperature measurement accuracy.

- Testing was additionally conducted in NETL's aerothermal test facility using test coupons with fan-shaped cooling holes over a range of pressures and blowing ratios. The measured overall effectiveness variations with pressure and blowing ratio amounted to engine metal temperature variations of 50 °C. When compared to testing conducted with a coupon that did not contain cooling holes, locally measured net heat flux reduction was shown to increase with an increase in blowing ratio to a value of 0.5, meaning that fan-shaped film cooling holes could reduce heat flux by 50%. Figure 6 shows the area-average overall effectiveness variation with pressure and blowing ratio for test coupons with fan-shaped film cooling holes.

- Modifications to the NETL high temperature, pressurized aerothermal test facility included the capability of controlling cooling air temperature. Elevated cooling air temperatures can now be achieved to generate more realistic coolant-to-mainstream density ratios which can be held constant through a range of operating conditions.

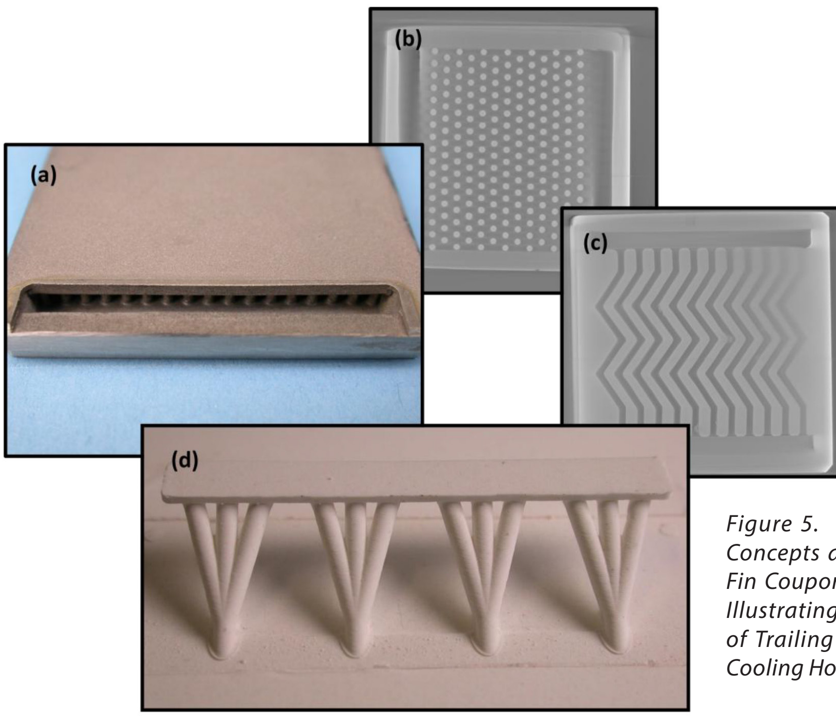

Figure 5. Commercial Production of NETL-RUA's Advanced Cooling Concepts at Mikro Systems Inc. (a) First Cast CM247 Fully Bridged Pin Fin Coupons; (b) CT Scan of Cast CM247 Fully Bridged Pin Fin Coupon Illustrating Absence of Blockage within the Pin Fin Array; (c) CT Scan of Trailing Edge Zig-Zag Cooling Configuration; (d) Tripod Hole Film Cooling Hole Core.

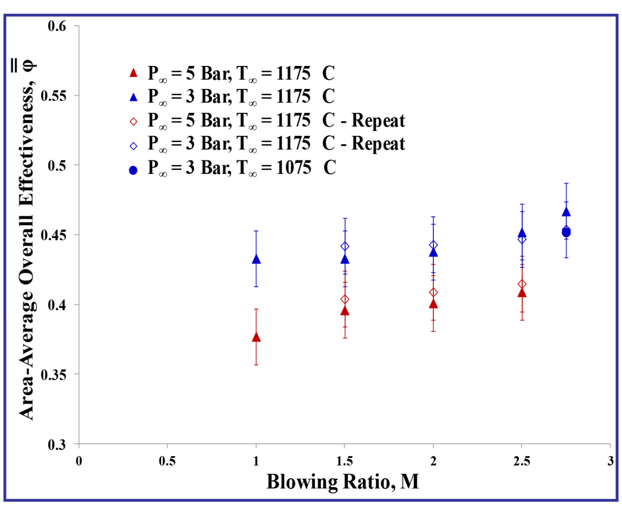

Figure 6. Area-Average Overall Effectiveness Illustrated as a Function of Blowing Ratio during Testing of Haynes 230 Coupons Containing Fan-Shaped Film Cooling Holes in NETL's High Temperature, Pressurized Aerothermal Test Facility.

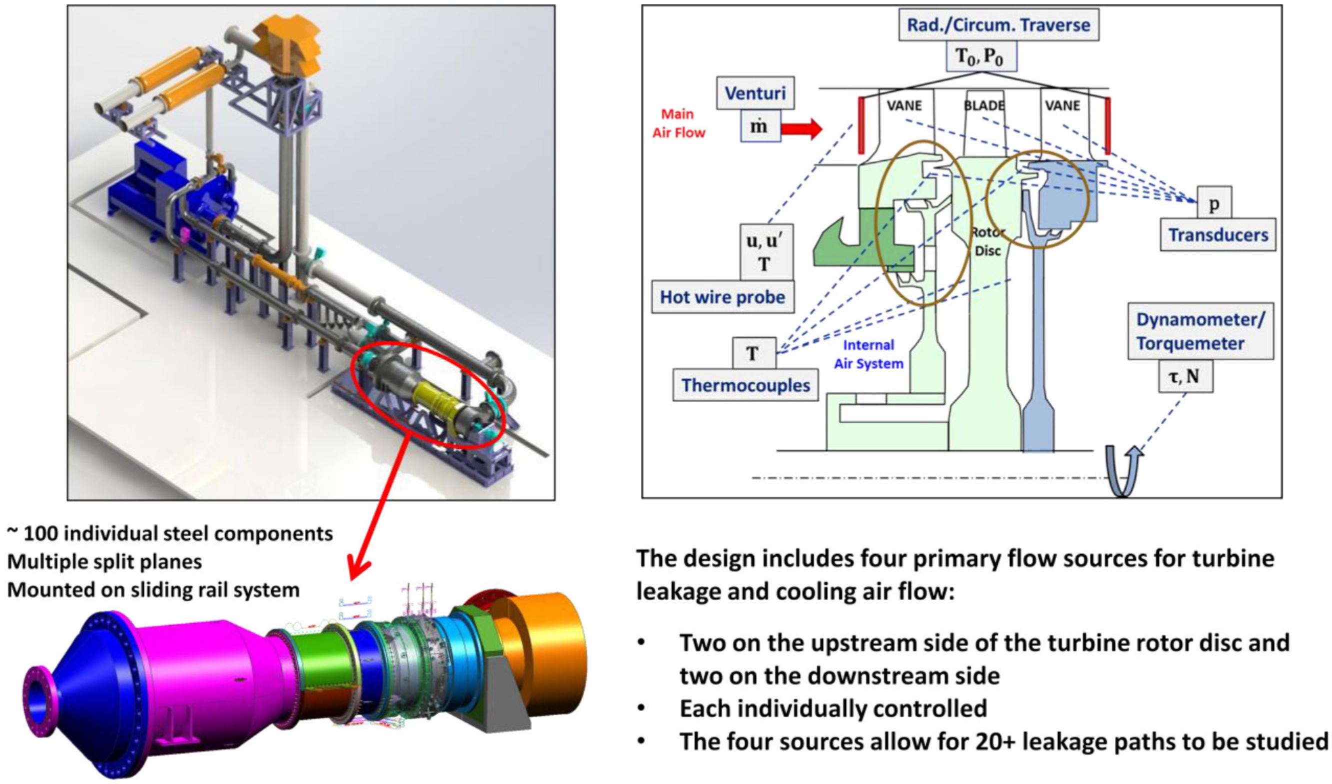

Figure 7. The New Secondary Flow Rotating Rig Design at Penn State has been Completed and Is Currently Being Manufactured and Assembled.

Secondary Flow Rotating Rig:

- The research team at Penn State officially moved into laboratory rooms and offices of the secondary flow rotating rig facility (Figure 7). Simultaneously, the electrical infrastructure and outdoor substation was completed for supplying power to two 1500 HP compressors.

- The compressor cooling system, turbine cooling system, dynamometer and water break system, telemetry system, pipe and air flow ductwork system, and magnetic bearing system were procured.

- Individual part drawings and 3-D solid modeling were completed for all facility and rig parts including all primary and secondary systems. Design reviews of all parts were conducted. The pipe ductwork system was designed in accordance with ASME B31.3-2002 Process Piping - Code for Pressure Piping. An overall facility and rig instrumentation plan was developed. Phase 1 (2014-2015) and Phase 2 (2015 - 2016) test conditions were identified and developed into the design package.

- Additive manufacturing methods/vendors for turbine vane construction were investigated and used to fabricate the airfoil vanes with integral instrumentation features. Example trial vanes were procured to allow evaluation of the integral instrumentation features. Over sixty Pratt & Whitney cast blades were also procured. A purchase order was issued for turbine disk forging and machining. Manufacturing has begun at multiple vendors on all steel hardware components that comprise the turbine test section.

- With respect to the pipe ductwork system, request for vendor quotes, competitive bidding, bid awarding, and purchase orders were completed. Manufacturing, plant visit and process reviews were conducted. Outdoor cooling system components were installed. Design and integration of programmable logic control system is in progress. Facility roof penetration locations were identified and prepared/framed. Facility roof platform equipment was acquired. Instrumentation acquisition is in progress (small sensors and large meters). Flow control valves were investigated, vendor bids were obtained, and procurement is in progress. Construction of the two steel chambers located upstream and downstream of the turbine test section is on-going. These chambers serve to condition the pressurized air flow.

- The gas tracer system has been identified (CO_2 injection into purge and leakage flow paths), acquired and benchmarked using a bench-top test stand. The PLC system design is in progress with Penn State's Applied Research Laboratory to design, build, and test the facility PLC control system by December 2013. PLC hardware has been identified and price quoted. The input and output specifications (electrical and physical) are currently being cataloged for all facility equipment items and facility operational instrumentation to help in the design of both the PLC system and the data acquisition system. In addition, calibration standard equipment was procured.

Benefits

This NETL-RUA project supports DOE's Turbine Program that is focused on development of gas turbines that can be operated on coal-based hydrogen fuels, while increasing the combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. This research is expected to render measurable outcomes that will help meet these goals plus a 30 percent power increase above the hydrogen-fired combined cycle baseline. In addition, knowledge gained from this project will further advance aerothermal cooling and TBC technologies in the general turbine community.