the ENERGY lab

PROJECT FACTS

Hydrogen Turbines

Analysis of Gas Turbine Thermal Performance—Ames Laboratory

Background

Developing turbine technologies to operate on coal-derived synthesis gas (syngas), hydrogen fuels, and oxy-fuels is critical to the development of advanced power gener-ation technologies such as integrated gasification combined cycle and the deployment of near-zero-emission type power plants with capture and separation of carbon dioxide (CO_2). Turbine efficiency and service life are strongly affected by the turbine expansion process, where the working fluid's high thermal energy gas is converted into mechanical energy to drive the compressor and the electric generator. The most effective way to increase the efficiency of the expansion process is to raise the temperature of the turbine's working fluid. However, the higher temperatures exceed the maximum temperature the state-of-the-art turbine material systems can withstand while maintaining structural integrity and operational reliability. Thus, cooling—such as internal, film, and impingement—is essential for all parts of the turbine whose surfaces contact the hot gases.

Ames Laboratory (Ames Lab) and Purdue University are exploring advanced cooling strategies to respond to the challenging nature of turbine hot gas path component design. Today's turbines are designed to operate very close to the maximum allowable temperatures of their materials of construction and must meet current industry goals to greatly reduce cooling flows to further increase system efficiency. These cooling component designs are further challenged by the combustion of high-hydrogen fuels and oxy-fuels, which increase turbine heat transfer characteristics due to the increase water vapor content, elevated erosion and deposition tendencies, and much higher hot-gas mass flow rates. These combined aero-thermal challenges illustrate the importance of maximizing the available cooling within the application of advanced cooling strategies.

This project is managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). 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 these tech-nologies to achieve power production from high hydrogen content fuels derived from coal that is clean, efficient, and cost-effective, minimizes CO_2 emissions, and will help maintain the nation's leadership in the export of gas turbine equipment.

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PARTNERS

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PROJECT DURATION

Start Date	End Date
10/01/2004	09/30/2013

(annual continuations)

COST

Total Project Value
$995,000

DOE/Non-DOE Share
$995,000/$0

AWARD NUMBER

ALO5205018

U.S. DEPARTMENT OF ENERGY

Project Description

Ames Lab and Purdue University are developing cooling strategies through the following tasks:

- Develop and evaluate computational fluid dynamics (CFD)-based analysis tools that can be used to study heat transfer issues in the design of turbine components and develop guidelines and best practices for their use.
- Examine the basis of the experimental methods used to validate CFD design and analysis tools.
- Apply CFD analysis tools to support the development of turbine technologies for advanced, near-zero emission-type coal-based power systems. The analysis tools of interest are those that can properly account for the steady and unsteady three-dimensional heat transfer from the hot gas in the turbine blade/vane passages through the turbine material system (thermal barrier coating and superalloy) to the internal cooling passages as a function of the cooling strategy as well as a function of the hot-gas and coolant compositions, mass flow rates, and temperatures.

Goals and Objectives

The goal is to develop an analysis tool that can be used to examine and explore heat transfer design issues of turbine components to support the development of turbine technologies for advanced coal-based power systems. The tool will consider heat transfer from the hot gases to the turbine material system as a function of the cooling strategy, fuel used, amount and nature of diluents used to control combustion and formation of nitric oxides, mass flow rate, firing and turbine inlet temperatures, and the thermodynamic cycle.

Accomplishments

- Performed CFD simulations that showed that if the Biot numbers of two geometrically similar configurations are nearly the same in magnitude and distribution on both the hot and cold sides of a turbine material, then the magnitude and contours of the normalized temperature and heat flux within the turbine material would be nearly the same. This analogy enables experimental studies of turbine cooling designs at near room temperatures and pressures with greatly scaled-up geometries to allow for more detailed interrogations that provide insight into turbine cooling performance (as if the experiment was conducted under realistic turbine operating conditions with high temperatures, high pressures, and the correct dimensions).
- Examined three approximations for bulk temperature that are widely used in experimental measurements of the heat transfer coefficient. The work showed that linear interpolation only gives accurate results in straight ducts with an error of less than 3 percent if the flow is turbulent, the two planes where the bulk temperatures are measured are taken in the fully-developed region (i.e., not in the entrance transition region), and the distance between the two planes where linear interpolation is employed is 20 duct hydraulic diameters or less. Other approximations based on the inlet temperature or an averaged bulk temperature give grossly inaccurate results.
- Performed initial CFD studies to understand how 'pin fins' clearance height-to-diameter ratio and height-to-diameter ratio affect surface heat transfer and stagnation pressure.
- Performed a study on the flow and heat transfer in the entrance region of a smooth circular duct and the entrance region of a rectangular duct lined with an array of pin fins.

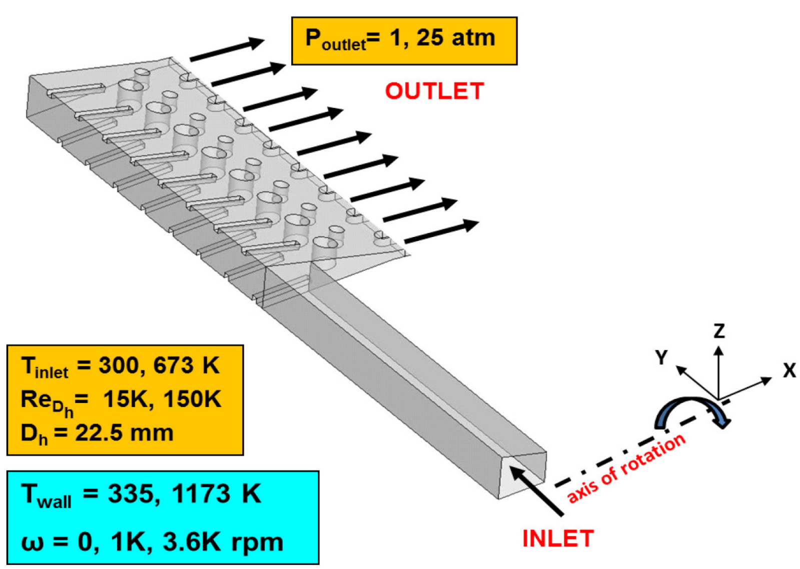

Figure 1. Schematic of the wedge-shaped duct with ribs and pin fins for the trailing edge of a turbine vane/blade.

During this effort a new nondimensional parameter, called the SCS number was proposed and contrasted with the traditional Nusselt number (Nu). The SCS number has the advantage of not requiring the bulk temperature, which is difficult for the experimentalist to measure. For Nu, the history is embedded in the bulk temperature (Tb). For SCS, the history is built into the SCS number itself. Thus, the magnitude of SCS is also a measure of the "capacity" of the fluid to cool or heat the wall. The SCS may be preferred for quantifying heat-transfer measurements since there will no ambiguity in the Tb used to define heat-transfer. However, when designing heat exchangers, Nu is preferred because Tb is clearly defined. Thus, a formula was developed to convert SCS to Nu and vice versa.

- Performed a time-accurate conjugate CFD study to understand the unsteady flow and heat transfer in and about a nickel-based super alloy plate heated on one side by a specified heat flux and cooled on the other side by an array of impinging cooling jets with varying heating and cooling loads. Though the cooling supplied ensures that the maximum temperature in the plate is equal to the maximum allowable material temperature when steady state is reached, it was found that the maximum temperature in the plate exceeded the maximum allowable temperature for a substantial amount of time. The duration of over temperature is a strong function of the heat capacity in the material and the variation of the heat-transfer coefficient along the cooled side of the plate.
- Performed CFD simulations based on steady RANS (Reynolds-averaged Navier-Stokes) closed by the shear-stress transport turbulence model to study the compressible flow and heat transfer in a wedge-shaped duct for the trailing-edge region of a turbine vane/blade under rotating and non-rotating conditions. The objective is to understand the flow mechanisms by which ribs and pin fins in the wedge-shaped duct turn radially outward flow of the coolant from the hub to flow uniformly in the axial direction to cool the entire duct. Results obtained show that pin fins can greatly reduce the size of the separated region when the coolant emerges from the inlet duct to enter the wedge-shaped duct. Also, pin fins provide flow resistance to control the uniformity of the flow along the cross section of wedge-shaped duct in addition to enhancing surface heat transfer via horseshoe vortices about each pin fin. A staggered array of square ribs that extend from the exit of the inlet duct to the tip of the wedge-shaped duct in the radial direction was found to create two sets of spiraling flows that causes the radial flow exiting from the inlet duct to spiral in the axial direction with one created by the stagnation region upstream of each rib and the other created by the separation downstream of each rib. When there is rotation, the staggered array of ribs was found to mitigate the adverse effects of centrifugal buoyancy by confining flow separation to be between the ribs on the leading face.

Benefits

This project supports DOE's Hydrogen Turbine Program that is striving to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by three to five percentage points over baseline, and reduce emissions. Studies by Ames Lab and Purdue University will increase the reliability of CFD-based analysis tools and thereby allow designers to minimize the critical heat transfer issues in the design of their turbine components.

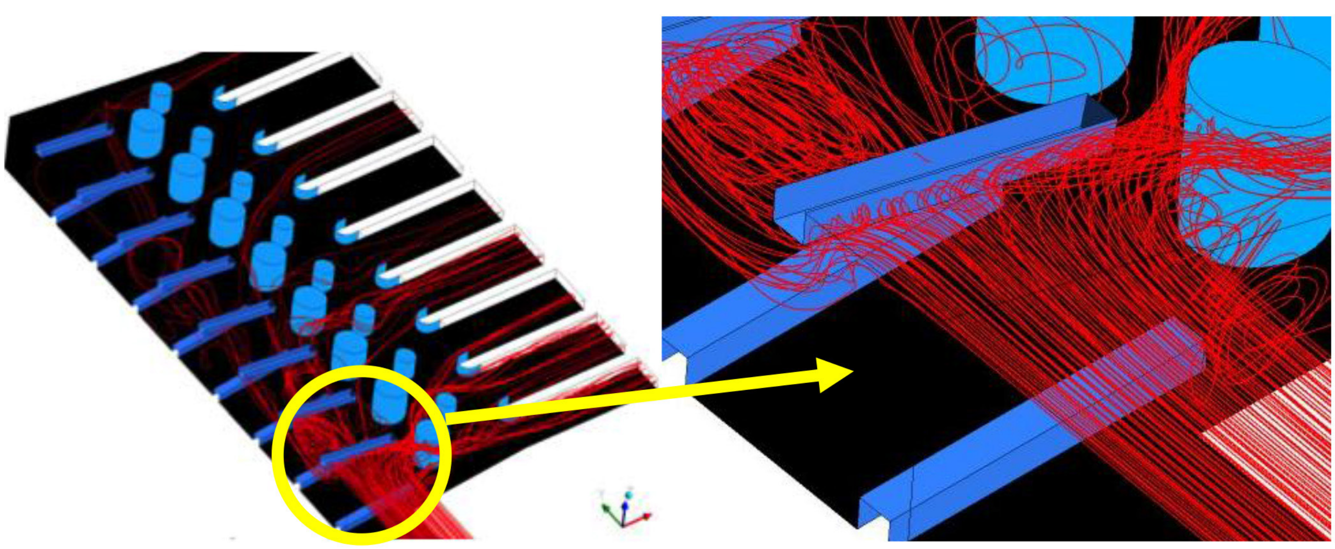

Figure 2. Streamlines showing how the ribs turn radially outward flow towards the axial direction.

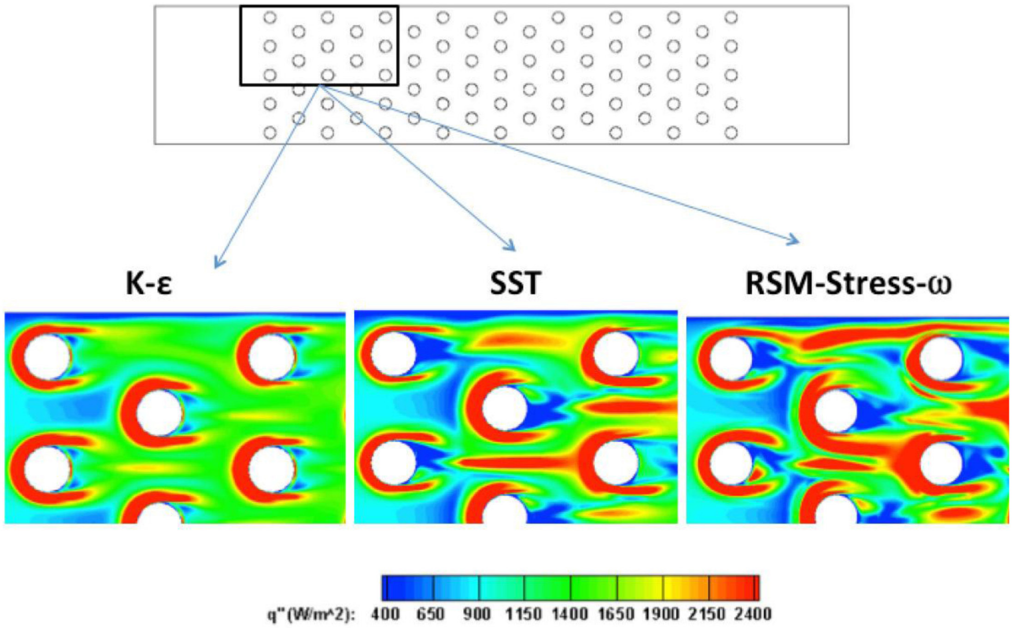

Figure 3. Heat Flux on the Wall Induced by Pin Fins as obtained by using the following turbulence models: realizable k-ε, shear-stress transport (SST), and full Reynolds stress model (RSM) with stress-omega in the near-wall region.