Deposition of Alternative (Syngas) Fuels on Turbine Blades with Film Cooling

FACT SHEET
Subcontract 05-01-SR120

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II. PROJECT DESCRIPTION

A. Objectives

This effort will address three critical technical issues associated with syngas use in gas turbines:
(1) The effects of syngas deposition, erosion, and corrosion at elevated temperatures
(2) The possibilities for deposit mitigation through surface sub-cooling
(3) The influence of deposition (and TBC residual) on film cooling flows

B. Background/Relevancy

Background. Turbine inlet temperatures for large power generation gas turbines have been steadily increasing over the last several decades due to significant advances in materials and cooling technologies. At the same time, political and economic pressures are pushing utilities to consider fuel flexibility. Compared to "clean" burning natural gas, these alternative fuels (e.g. coal, petcoke, biomass) have higher concentrations of trace elements and ash that present significant corrosion challenges to turbine operation. If combustion products arrive at the turbine blade surface in the liquid (or vapor) phase, it is likely that they will deposit (or condense) there and accelerate material corrosion. A number of studies conducted in the 1970's and 1980's (before the dominant use of natural gas in gas turbines) showed that corrosive deposition is strongly dependent on temperature. Depending on the syngas fuel employed, the threshold temperature for deposition varied from 900C – 1100C. Above this threshold, studies showed up to an order of magnitude increase in deposition rates. Since those tests were conducted, several key technologies (e.g. thermal barrier coatings, advanced cooling schemes, and single crystal blades) have permitted substantial increases in firing temperatures (up to 1400C). The compatibility of these advances with ash-bearing syngas fuels has yet to be assessed.

Relevancy. With this research program, DOE and industry will gain valuable insights into factors affecting the safe, efficient operation of modern industrial turbines with alternative fuels.

Findings may also be used to help establish maintenance guidelines and gas cleanup specifications for IGCC plants. Ultimately, this will reduce the time and cost to certify and commercialize modern gas turbines operating with syngas fuels.

C. Period of Performance. 1 Aug 2005 – 31 July 2008 (no cost extension to 31 Jan 2009)

D. Project Summary

Under the University Turbine Research (UTSR) program, Brigham Young University is investigating the negative impacts of alternative fuel use in modern gas turbines. In Phase 1, deposition studies will be conducted in BYU's accelerated turbine deposition facility to document the influence of temperature on deposition, erosion, and corrosion from syngas fuels. This research will be conducted by seeding a natural gas combustor with coal and biomass products of combustion and accelerating them onto target turbine materials. Combustion byproducts will be prepared from industry donations and/or BYU's operating coal and biomass reactors. BYU's accelerated turbine deposition facility matches both the impact velocity and gas temperature of modern industrial turbines. Arrangements are in place with industrial contacts at GE, Solar, Praxair, and Siemens to make available modern turbine materials and coatings as targets for this study. Once syngas deposits are formed on the target, various analyses will be conducted, including: surface mapping, roughness assessment, deposit thermal conductivity measurement, and elemental decomposition with corrosion assessment. Elemental analyses will employ existing diagnostic equipment including: scanning electron microscopy, inductively-coupled plasma with atomic absorption, and x-ray analysis for quantitative analysis of deposits. Phase 1 of the proposed research will also explore the possibility of sub-cooling the turbine surface to mitigate deposition. This will be accomplished by cooling the backside of the target coupon, similar to internal convection cooling in a turbine blade.

Phase 2 will evaluate the influence of deposit formation on film cooling flows. This study will be accomplished in the same turbine deposition facility by injecting coolant from film holes in the target coupon. Sections of turbine blades with cooling holes will be solicited for this effort so that the coolant hole geometry is representative of current practice. Deposits in and around cooling holes will be measured and analyzed.

During the optional 3rd year of the research program, scaled models of the deposit-laden film holes will be installed in a low-speed wind tunnel at BYU for flow and heat transfer assessments. A 3-D PIV system and IR camera will be used to gather 3-dimensional velocity data as well as surface heat transfer and film effectiveness. The data density available from these sophisticated diagnostics will provide an important database for CFD validation. This phase will also consider the effects of TBC residue left in film holes during the plasma-spray application process since it is likely that this residue bears resemblance to deposits formed during turbine operation.

III. PROJECT COSTS

$399,422

IV. MAJOR ACCOMPLISHMENTS SINCE BEGINNING OF PROJECT

- Facility redesign to allow backside impingement and film cooling of turbine test articles was completed (see Fig. 1). Validation testing has been successful.
- Completed testing sequence to measure deposition rate (particulate capture efficiency) as a function of flow temperature in the absence of test article cooling. There is a clear threshold for particle deposition beginning near 1000C. This result is consistent with previous work by BYU and others.
- Completed testing sequence to measure deposition rate (particulate capture efficiency) as a function of particulate size at a constant gas temperature of 1150C (no cooling). Deposition

appears to reach an asymptote at low particle diameters consistent with those that typically make it through filtration systems (~3μm).

- Completed testing sequence to measure deposition rate (particulate capture efficiency) as a function of cooling rate at a constant gas temperature of 1150C (no cooling). Testing was conducted with both petcoke and coal particulate. Cooling is provided from backside impingement (as shown in Fig. 1) and produces a dramatic reduction in deposition with increased cooling. Backside surface temperatures (measured with a welded thermocouple) are also shown falling with increased coolant. The data show a factor of four reduction in deposits for a 360°C drop in backside temperature (100°C drop in frontside temperature) with cooling. These results clearly show the benefits of cooling in reducing deposition.
- Completed post-test analyses of deposition specimens using ESEM showing evidence of TBC spallation and deposit crack penetration. Post-test analyses also included surface topography measurement. In nearly all cases, roughness variations are proportional to deposit thickness variations.
- Explored simultaneous optical measurement of both front and backside surface temperature to enable real-time estimates of deposit thermal resistance during the deposition process.
- Studied accelerated deposition with film cooling. Parametric studies were conducted with both hole spacing and blowing ratio. Large hole spacing allows deposit buildup between the film flow trajectory. Increased blowing ratio lowers the metal surface temperatures throughout due to the higher coolant massflow rate. Thus, deposition falls off with increasing blowing ratio similar to the observed behavior with backside impingement cooling alone. The mechanism for deposit buildup is documented using optical surface temperature measurement using a digital camera. The regions between film holes are more susceptible to deposition due to higher temperatures. Initial deposition creates an active site for further deposition since the deposits are thermally insulated from the cooler coupon surface and are extended into the hot gas path. At small hole spacing, deposition is mitigated due to improved film coverage.
    - Shaped holes with a spacing of 3d were found to be especially deposition resistant for all blowing ratios due to the uniform spanwise coverage of the coolant flow.
    - Time-lapsed images of the deposition growth (Fig. 2) show a non-linear increase in surface coverage. Deposits begin as a local phenomenon and then grow upstream as particles collide with the initial deposition site. Thus, once the initial deposits are formed, the deposition rate increases rapidly. Figure 3 shows the variation of deposit coverage with time throughout the test sequence.
- Fabricated 20x scaled models of three different film hole deposit patterns (Fig. 4). Heat transfer studies were conducted with the roughness models in a low speed wind tunnel at OSU. Both the film cooling effectiveness and convective heat transfer coefficient were measured over a blowing ratio range of $0.5 < M < 2.0$.
    - Compared to a smooth companion model, deposit roughness located primarily upstream of the film holes enhances the effectiveness of high blowing ratio film cooling. Jet blow-off is mitigated significantly and heat transfer levels in the region downstream of the roughness features are generally lower as well.
    - For the scaled models with deposit roughness located primarily between the coolant holes, spanwise (lateral) diffusion of the coolant is severely restricted (Fig. 5). Centerline effectiveness values remain high and heat transfer levels are everywhere increased.

- Conducted two-dimensional CFD simulation of accelerated deposition facility using FLUENT. Incorporated deposition model with temperature sensitivity of particulate Young's modulus tuned to match experimental data trends. Doing so allows excellent agreement with capture efficiency data from experiments (Fig. 6).

V. MAJOR ACTIVITIES PLANNED DURING THE NEXT 6 MONTHS

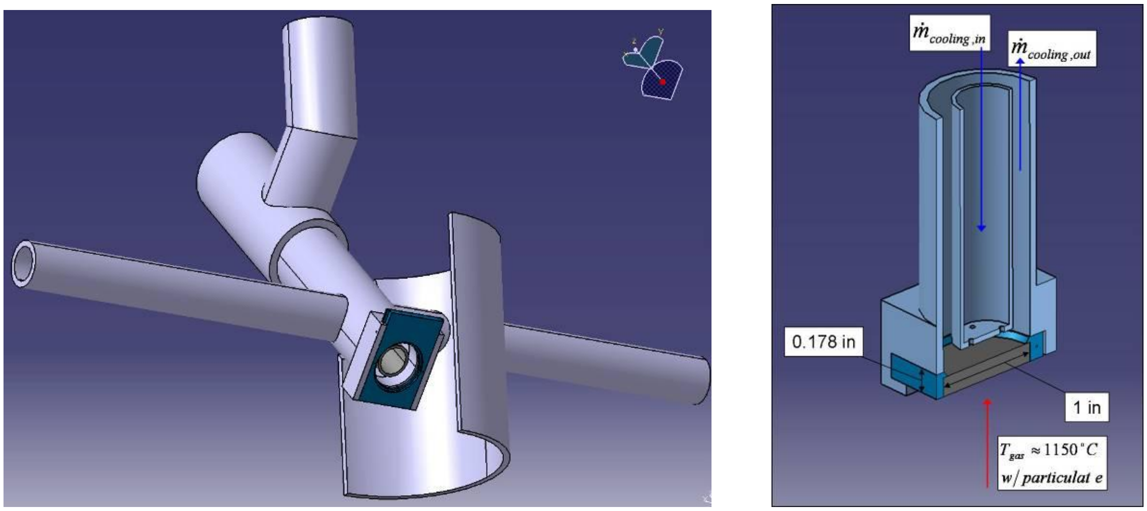
- Continue deposition model studies using PIV to study flowfield.
- Continue deposition modeling initiative.

VI. ISSUES

- None

VII. ATTACHMENTS

See figures 1-6 below.



(a) Redesigned coupon holder **(b) Impingement Cooling**

Figure 1: TADF test coupon holder redesign with backside cooling.

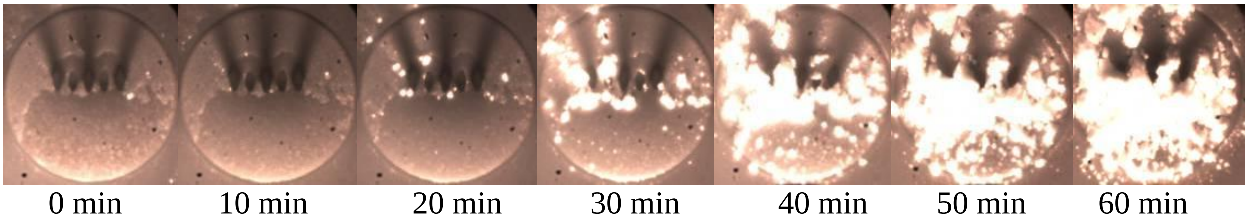


Figure 2. Deposit development with the elapsing time at the value of M=2.0. Flow is bottom to top.

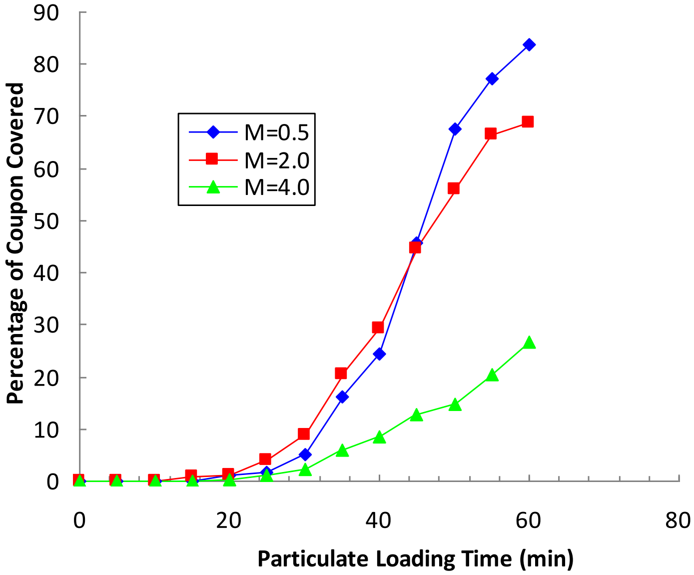
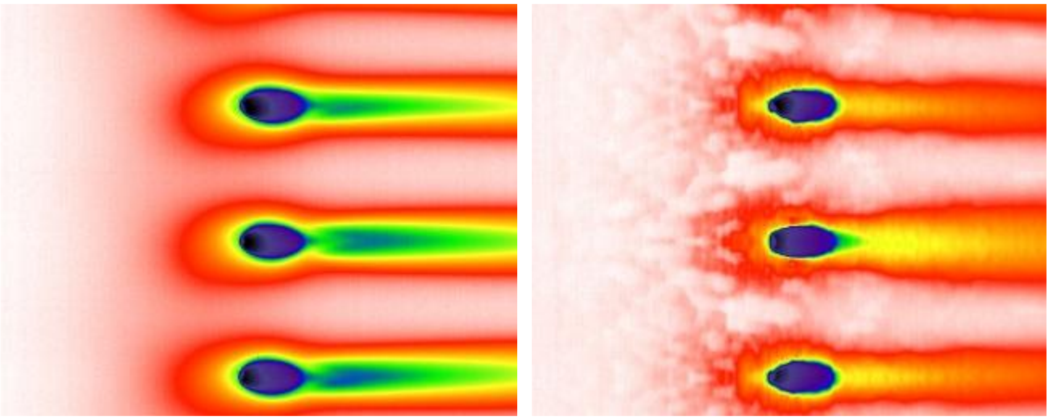


Figure 3. Influence of blowing ratio (M) on deposit surface coverage at a set particulate loading rate.

(a) s/d=3.0 **(b) s/d=3.37** **(c) s/d=4.5**

Figure 4: After deposition test photographs of the three turbine blade coupons that used for scale model generation.



(a) smooth **(b) rough**

Figure 5: Steady state surface temperature maps for M=0.5 on the s/d=4.5 film cooling model: smooth vs. rough wall condition. Flow is left to right.

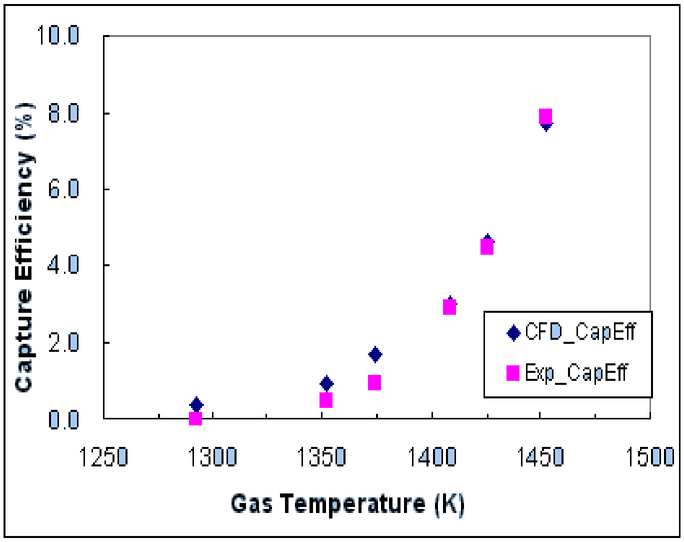


Figure 6. Measured and modeled capture efficiency as a function of temperature.