Introduction of Clean Power and Energy Research Consortium (CPERC)

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Abstract

A Clean Power and Energy Research Consortium (CPERC) was established in 2003, under the *Louisiana Governor's Energy Initiative*, to help address critical scientific issues in power and energy generation. Of specific interest are technologies that will permit greater efficiencies, greater reliability, lower emissions and the effective utilization of alternative fuels. Core expertise and well-established research programs in these areas already exists at **seven universities in the state of Louisiana**, and CPERC aims to bring these groups together to exert impact on clean power production at both state and national levels. In 2005, CPERC was named as the National Center of Excellence in the Energy Bill. CPERC consists of:

- Turbine Innovation & Energy Research (TIER) Center at Louisiana State University
- Audubon Sugar Institute (ASI) at LSU AgCenter.
- Bio-Energy Laboratory (BEL) at Nicholls State University,
- Advanced Materials Research Lab (AMRL) at Southern University,
- Tulane Energy Institute (TEI) at Tulane University,
- Bioprocessing Research Laboratory (BRL) at University of Louisiana at Lafayette,
- Energy Conversion & Conservation Center (ECCC) at University of New Orleans.

Each Center/Laboratory has core research expertise in specific energy areas, and CPERC harnesses this expertise in a collaborative manner to establish a national center of excellence in clean energy with emphasis on the hydrogen and alternative fuel economy.

CPERC will deliver the following benefits to Louisiana: (1) CPERC will be a national center of excellence and will provide a boost to ongoing research activities in power generation, emissions control, and biofuels production; (2) CPERC will lead the nation in the development of new technologies for the clean fuels industry with emphasis on clean power generation and utilization of renewable resources to lower energy costs, improve reliability, and reduce emissions and crude oil imports; and (3) CPERC will provide the state and its industrial base an educated and trained workforce in all aspects of energy and power generation. Louisiana is rich in fossilized and renewable resources, and thus has a vested interest in technologies that utilize these.

CPERC's goal is to develop technologies which will lead to a reduction of oil imports and fuel consumption by 10 percent. This would create an estimated savings in natural gas costs alone of more than *$5 billion/per year* and reduction in greenhouse gas emissions of about 10 million metric tons nationwide. It is estimated that Louisiana would benefit from fuel cost savings of approximately $300 million a year.

CPERC will involve high-end technologies dealing with hydrogen-driven energy generation systems, micro-systems, materials, bio-energy, and environmental pollution, and is likely to lead to small-scale spin-off companies that will provide components, parts and services to the gas turbine, power generation, renewable fuel, petrochemical, and related industries.

Introduction of Turbine Innovation and Energy Research Center (TIER)

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The Turbine Innovation and Energy Research (TIER) Center focuses on the hot gas path of the gas turbine engine, and the research undertaken aims to improve efficiency, explore fuel flexibility, reduce emissions, improve reliability and reduce operational costs. TIER laboratories occupy nearly 13,000 sq ft of renovated space and houses a series of laboratories. Some example laboratories include:

a. Combustion laboratory that houses several combustor rigs
b. Rotating turbine rig facility for internal cooling studies
c. High pressure, heated cascade test facility
d. Low pressure nozzle guide vane facility
e. Blade tip cascade facility
f. Single stage rotor facility for blade tip and shroud studies
g. High temperature materials/material-coating facility
h. Computational fluids, heat transfer and combustion laboratory

In this presentation, activities in each of the laboratories are briefly described. The focus is on fuel flexibility in combustors, reduced coolant usage, higher-temperature materials and material coatings, reduced aerodynamic losses and reduced operational costs.

Fig. 1: Combustor Facility

Fig. 2: Picture of TIER Lab Building (left) and Compressed Air Storage (right)

Exploring Biofuels and Hydrogen for Combustion Engines

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Due to depletion of fossil fuels and their impact on environment especially green-house-gas (GHG) emission, renewable and clean energy sources are getting significant attention, served as one of energy solutions that help us address current energy and also environment concerns. Petroleum is still the largest energy source consumed by the world's population. Apart from environmental problems, the other issue is the uneven distribution of petroleum in the world. The present energy system is not sustainable because of equity issues along with environmental, economic, and geopolitical concerns. On the contrary, the renewable energy sources are distributed more evenly. Therefore, renewable energy sources such as biofuels, hydrogen, hydro, wind, solar, geothermal, and marine energy sources will be important entities in the world's future energy supply. Our research group put the emphasis on the understanding the fundamentals aspects of combustion behavior of biofuels along with energetic nanoparticles and different underlying issues with hydrogen combustion for utilizing these fuels as practical fuels for combustion engines.

Though biofuels (such as ethanol) are thought to be potential alternative energy sources, they have lower energy density than current transportation fuels. The lower heating value of ethanol is about 26.9 MJ/Kg which is considerably lower than that of gasoline (43.4 MJ/Kg) or kerosene (43.1 MJ/Kg). To make biofuels more cost-competitive, a potential strategy is to increase its energy density by synthetically adding higher-energy density additives. An alternative approach is to significantly reduce the cost of producing ethanol while still producing a practical fuel. This would result in reduced volumetric fuel economy but may offer an economic advantage. Current production of commercial grade ethanol contains 5% water, and is used routinely in gasoline engines, primarily as an additive, and is currently being considered for use in gas turbines.

Fuel additives have been often considered in order to enhance the performance of propulsion systems. Nano-sized metal powders are particularly attractive as potential fuel additives because of their higher energy densities, high specific surface area, and ability to store energy at the surfaces. Figure 1 shows a comparison of heating values of different metal or metalloid particles to ethanol. In this context, boron stands out due to its high heating value on both gravimetric and volumetric bases. However, the combustion of boron is inhibited (specifically, the ignition is delayed) by the initial presence of an oxide layer, and its high evaporation and boiling temperatures. The present study investigates the combustion behavior of commercially available boron nanoparticles and explores the underlying effects of the particle morphology and size on the combustion characteristics. The goal is to understand the burning characteristics of boron nanoparticles or their clusters, and to optimize the processing and the operational environment for complete boron combustion and the associated energy release. To give a representative idea of the thermal contribution from the boron combustion, the temeprature differences bewteen 'with' and 'without' boron have been shown (Fig. 2) for different boron loadings and compared with theoretical increase (adiabatic cases). The experimental data show almost a linearly increasing trend with increase in boron loading, which suggests enhanced heat release associated with use of boron nanoparticles.

In order to understand the role of hydrogen addition in flame structure and behavior, both confined and unconfined turbulent methane air premixed flames have been examined with different hydrogen levels during the extinction transition with high speed imaging of OH* chemiluminescence and planar laser induced fluorescence measurement of OH. The blowout conditions are approached by reducing the flow rate of fuel mixture or the equivalence ratio with constant air flow rate. The estimated extinction times from high speed imaging and corresponding flame structures are analyzed and compared between confined and unconfined flames with different hydrogen blends. Figure 3 shows hydrogen addition increases extinction time for unconfined flames, and reduces it for confined flames. Figure 4 shows with hydrogen addition, the fluctuation of OH*, that is, fluctuation of heat release rate, gradually decreases in unconfined flames while it increases in confined flames. These two shed important light on the behavior observed for the extinction time scales. Near Lean blowout limit (LBO), the unsteadiness represented by the RMS (OH*) or heat release increase with hydrogen addition in confined flames. The higher unsteadiness implies higher straining rates (assuming stress and strain are related) and therefore the thin flame fronts near LBO are subjected to the high straining and can be quickly extinguished leading to short extinction times. In unconfined flames, the RMS (OH*) levels actually decay with hydrogen addition, and this implies that the flame fronts are subjected to lower straining at higher hydrogen levels for the unconfined flames leading to longer extinction times.

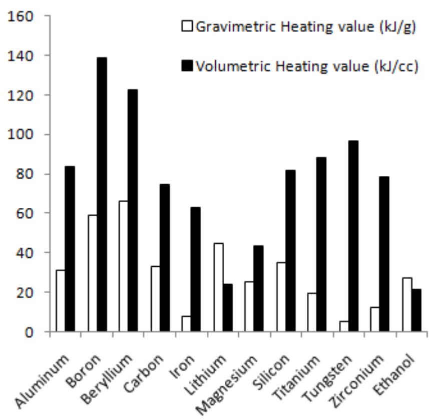

Fig. 1 Heating values of different fuels

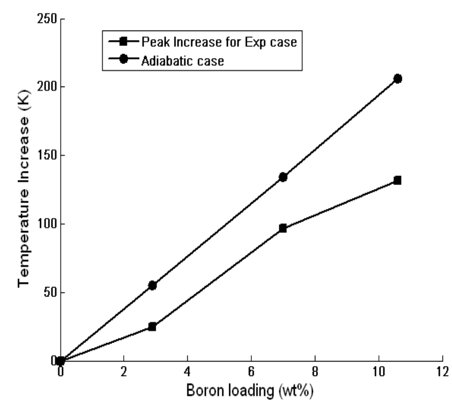

Fig. 2 Temperature increase with Boron

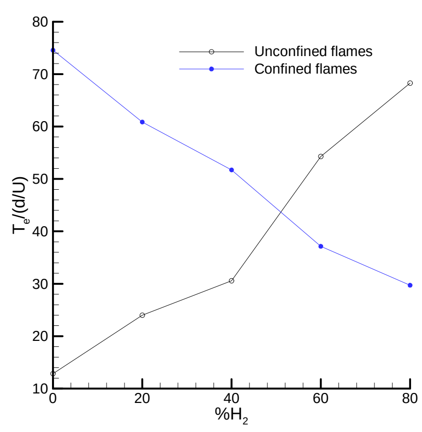

Fig. 3 Estimated extinction time T_e

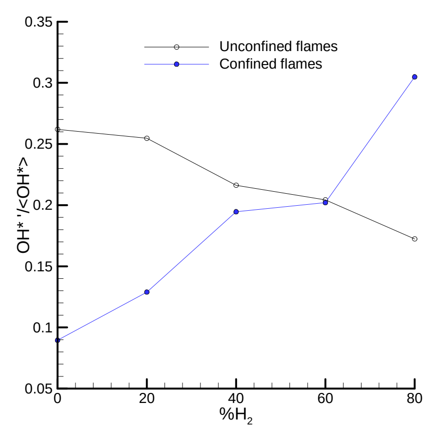

Fig. 4 OH* fluctuation

Advanced Cooling Concepts in Turbomachinery

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A significant improvement in overall gas turbine engine efficiency occurs when turbine stage inlet temperatures are increased, but material limits of the turbine blades require improved cooling schemes and technological advancements to the materials themselves. The leading practical cooling schemes can be divided into two main types: internal and external. External cooling schemes comprise of methods that directly interact with the hot gas path (HGP). Internal cooling schemes involve the use of cooling air redirected from the turbine compressor or, in the case of land based turbines, the use of cooling water. Several innovative and unique cooling schemes and test methods are examined.

The pressure drop and heat transfer in a two pass internal cooling channel with two different bend geometries is experimentally studied with the goal of improving the Thermal Performance Factor (TPF) in the internal coolant channel. The geometries studied are: (1) a baseline U-bend geometry with a rectangular divider wall, (2) a symmetrical bulb at the end of the divider wall, and (3) a combination of the symmetrical bulb and a bow on the opposite outer wall leading to a shaped flow contraction and expansion in the bend. Tests are conducted for four Reynolds number ranging from 10000 to 55000. The symmetrical bulb eliminates the separation due to the sharp turn and makes the heat transfer distribution in the bend portion more uniform. This modification reduces the bend pressure drop by 37% and augments the TPF by nearly 29% compared to the baseline case. The combination of bulb and bow case increases the local heat transfer in the bend region significantly, and reduces the bend pressure drop by nearly 27% leading to an augmentation of the TPF of 32% compared to the baseline case. These improvements in TPF point to the benefits of using the improved bend designs in internal cooling channels.

Heat transfer results for a given slot shaped channel with a 3:1 aspect ratio are presented using various trapezoid shaped spiral wound strips to enhance swirl and tumble motion in a simulated turbine blade internal channel. The Reynolds numbers investigated range from 10,000 to 50,000 and are based on the characteristics of the fluid at the channel inlet. A combination of thermochromic liquid crystal techniques and thermocouples were used to create a temperature vs. time map. Duhamel’s superposition theorem was then used to determine the local heat transfer coefficients (h) and heat transfer enhancement factors (Nu/Nu_o). Two different inlet geometries were tested and three combinations of helical strips were tested using a single, double, and pentuple spiral design. The results for these tests show average heat transfer enhancement values for the entire channel (Nu/Nu_o) greater than three at the higher Reynolds numbers and low normalized friction factors.

The TIER center’s heated vane cascade facility consists of an actual natural gas-fired combustor that heats high-pressure air (up to about 1000°F or 520°C) which then flows through a stationary vane + endwall cascade test section machined from stainless steel. Film cooling air bled from a location upstream of the combustor is fed through small holes machined on the test section. Instrumentation used in this rig include pressure taps, heat flux gages, and infrared (IR) imaging. Achievable engine-like conditions include blowing ratios (*M*) between 1.0 - 3.0 and density ratios (*DR*) from 1.2 to 2.0. While previous work focused on steady-state interactions, current research examines the transient behavior of these coolant-to-mainstream interaction.

Blade Tip Aerodynamics and Heat Transfer in Rotating Blades

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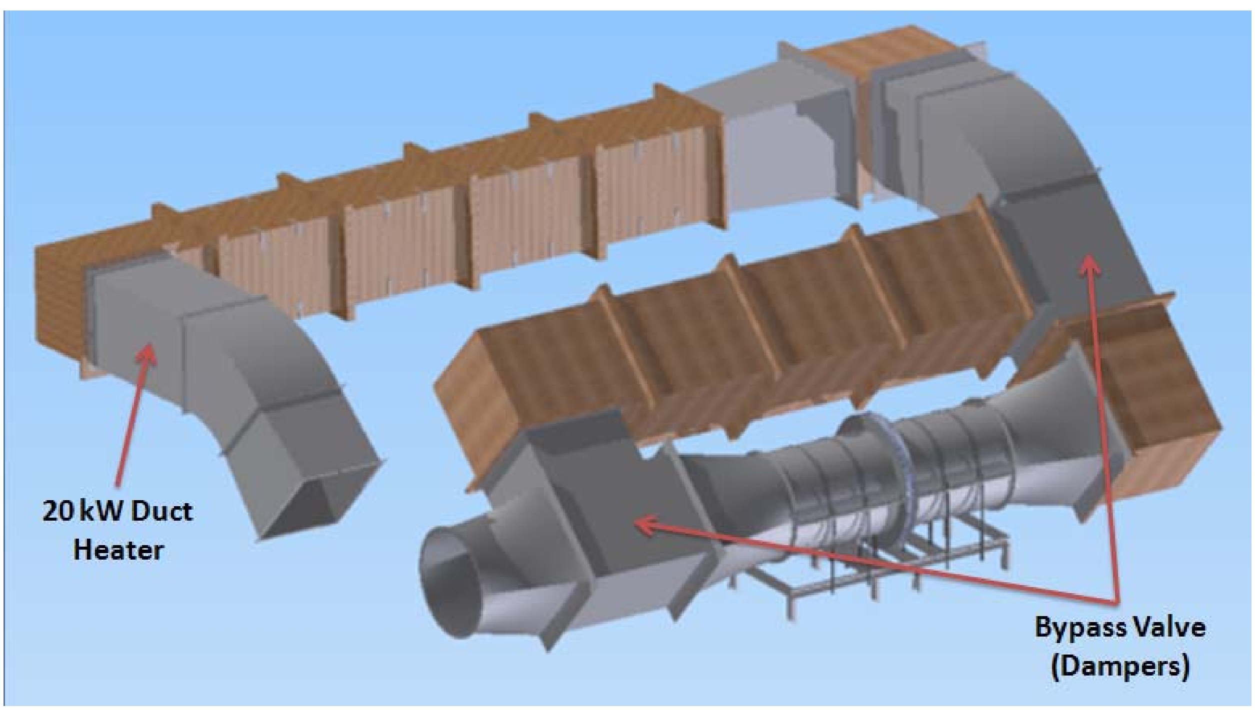
One way to increase the efficiency of a gas turbine engine is to increase the turbine inlet temperature. Today, hot gas temperatures in gas turbines exceed the melting point of the materials used to manufacture the turbine rotors. To avoid melting the rotor blades in the turbine, a thin layer of air, bled from the compressor, is used to form a protective barrier actively cooling the blades. The first section of a turbine blade to fail is the tip region where the tip vortex causes high rates of heat transfer and a hot spot forms toward the leading edge of the blade. In order to reduce the tip leakage flow a squealer rim has been employed to form a labyrinth seal with the shroud. Although tip leakage flow and heat transfer have been widely studied, the experimentation has been mostly limited to stationary vane cascades which neglect the effects of rotation and Coriolis forces.

To study the heat transfer within the squealer cavity on the blade tip, a film-cooled rotating vane cascade has been fabricated. A closed loop wind tunnel has been designed with a bypass loop. This will allow the free-stream air to heat up in the bypass while leaving the test section at a constant temperature. When the bypass gate is opened, the free-stream air temperature in the test section would be heated resulting in a step change in the air temperature. Liquid crystal thermography will be used to find the temperature history of the blade tip while in rotation. A high-speed camera will be used to take pictures of the blade tip. The rotor blades have a hollow cavity where the coolant air, passing through a hollow shaft and hub, is ejected through the film cooling holes. A transient 1-D semi-infinite analysis will be used to find the heat transfer coefficients and film cooling effectiveness.



Output Power Augmentation by Employing Gas Turbine Inlet Fogging/Overspray and Discussion of Associated Issues

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The output and efficiency of gas turbines are reduced significantly during the summer, especially in areas where the daytime temperature reaches as high as 50°C. Gas turbine inlet fogging and overspray has been considered as a simple and cost-effective method to increase the power output. Investigation was made on the inlet fogging on the gas turbine system performance using in-house developed software FogGT. This software is further extended to develop stage-by-stage wet-compression theory for overspray and interstage fogging that includes the analysis and effect of pre-heating and pre-cooling at each small stage inside the compressor. An algorithm has been developed using the thermal equilibrium method to calculate local velocity diagram and perform one-dimensional stage-by-stage analysis of the inlet and interstage fogging effect on airfoil aerodynamics and loading, which is further extended to the non-equilibrium model in which the water droplets evaporation depends on the hydrodynamic and thermal residence times and may not reach saturation at the end of stage. Investigation is also made on 3-D study of wet compression by incorporating droplet break-up, coalescence and a liquid droplet erosion model. The predicted erosion provides information of the erosion distribution on both vanes and blades in a rotating compressor stage.

This study further investigates the effect of silencer on fogging effectiveness. The fogging device can be installed either upstream or downstream of the silencer. Placing the fogging device upstream of the silencer can cause the silencer to intercept water droplets on the silencer baffles and lose cooling effectiveness. Placing the fogging device downstream of the silencer will raise another question on where the most effective location is, which can be determined by (a) investigating how many water droplets actually evaporate effectively to cool down the inlet air instead of colliding on the wall and draining out (i.e. fogging efficiency) and (b) quantifying the amount of non-evaporated droplets that may reach the compressor bellmouth to ascertain the erosion risk for compressor airfoils if wet compression is to be avoided. Computational fluid dynamics (CFD) is employed to investigate the water droplet transport and cooling effectiveness with different spray locations such as before and after the silencer baffles. Analysis on the droplet history (trajectory and size) is employed to interpret the mechanism of droplet dynamics under the influence of acceleration, diffusion, and body forces when the flow passes through the baffles and duct bent. The results show that, for the configuration of the investigated duct, installing the fogging system upstream of the silencer is about 3 percentage points better in evaporation effectiveness than placing it downstream of the silencer, irrespective of whether the silencer consists of a single row of baffles or two rows of staggered baffles. The evaporation effectiveness of the staggered silencer is about 0.8 percentage points higher than the single silencer. The pressure drop of the staggered silencer is 6.5% higher than the single silencer.

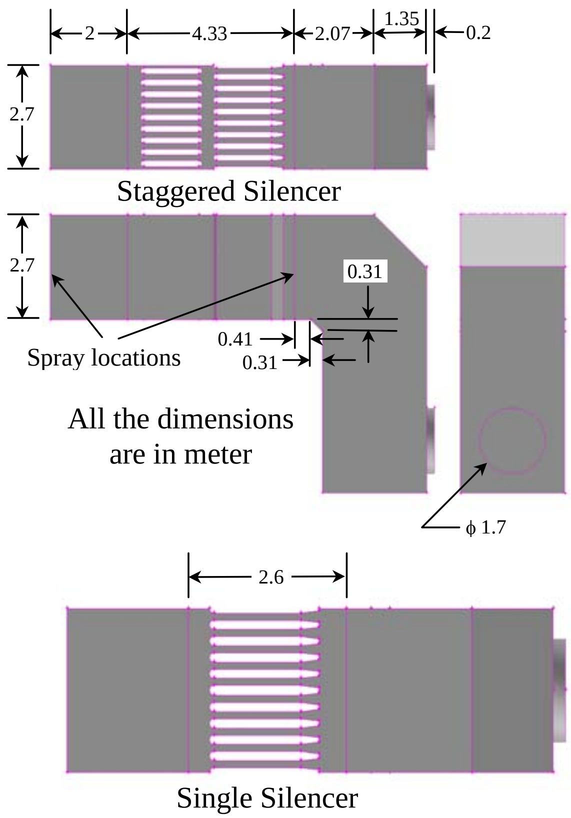

Figure 1 Dimension of the domain

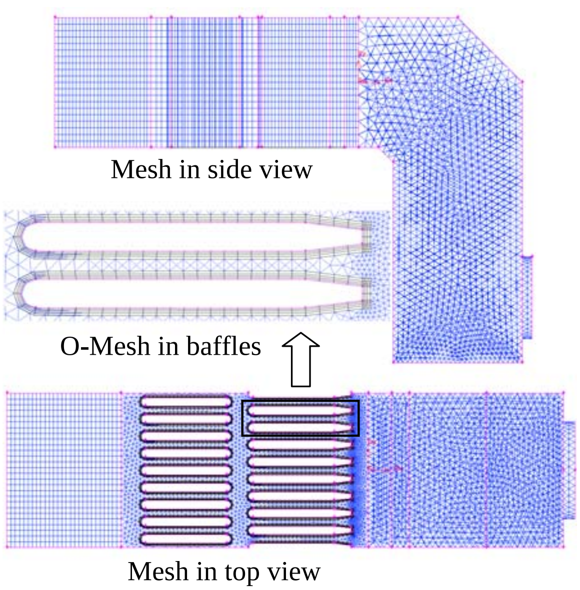

Figure 2 Meshed computational domain consisting of a mix of 231,000 structured and unstructured cells

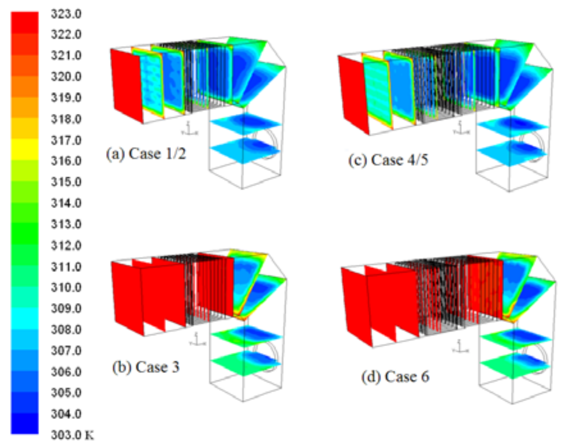

Figure 3 Temperature distributions for different cases on different axial planes

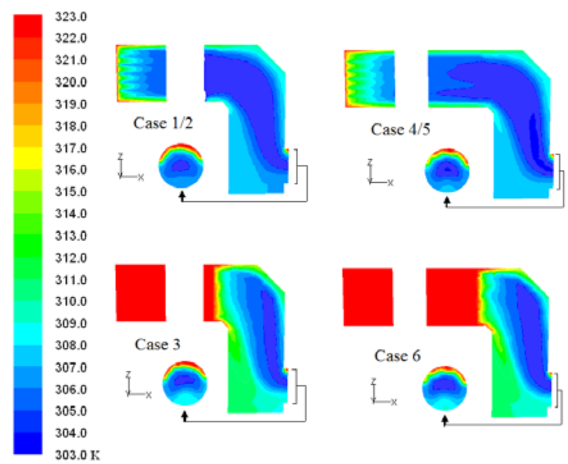

Figure 4 Temperature distributions for different cases on different axial planes

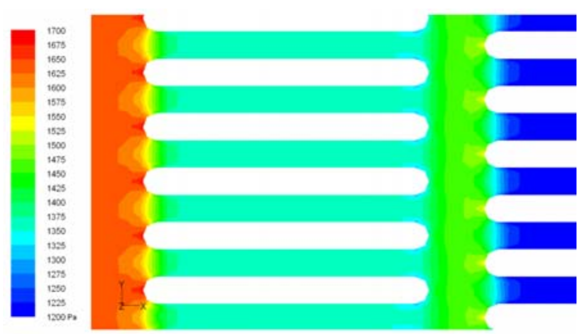

Figure 5 Static pressure distribution across the baffles

Co-Gasification of Coal and Biomass in IGCC Systems with Carbon Capture and Supercritical Steam Bottom Cycle

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In recent years, Integrated Gasification Combined Cycle Technology (IGCC) has been gaining steady popularity for use in clean coal power operations with carbon capture and sequestration. Great efforts have been continuously spent on investigating various ways to improve the efficiency and further reduce the greenhouse gas (GHG) emissions of such plants. This study focuses on investigating two approaches to achieve these goals. First, replace the traditional subcritical Rankine steam cycle of the overall plant with a supercritical steam cycle. Second, add different amounts of biomass as feedstock to reduce carbon footprint as well as the SO_x and NO_x emissions. In addition, the simulation is run while implementing several types of CCS, including post-combustion, sweet pre-combustion, and sour pre-combustion. All types studied use an amine-based removal system due to the similarity to the type of Acid Gas Removal (AGR) chosen for the baseline cases. In total, 32 separate cases were studied. Figs. 1 and 2 show the overall plant layout for the baseline case, with Fig. 1 having more emphasis on the gasification island, and Fig. 2 having more emphasis on the steam cycle.

Employing biomass as a feedstock to generate fuels or power has the advantage of being carbon neutral or even carbon negative if carbon is captured and sequestered (CCS.) However, due to a limited supply of feedstock, biomass plants are usually small, which results in higher capital and production costs. Considering these challenges, it is more economically attractive and less technically challenging to co-gasify biomass wastes with coal. Using the commercial software, Thermoflow®, this study shows that utilizing biomass with coal up to 50% (wt.) can, in one case, not only improve the efficiency (0.7 percentage points) and reduce overall emissions, but also be economically advantageous (reducing capital costs by \$350/kW and cost of electricity by 0.3 cents/kW-hr), as well. Supercritical steam cycles are always thermally (1.5 percentage points) and economically (\$700/kW, 0.4 cents/kW-hr) better than subcritical cycles. Table 1 shows the difference between the two plants for the baseline cases without CCS. Finally, for CCS, sour shift is the most feasible form of CCS, having similar reductions in carbon emissions (7,000 tons/MW-yr) to the other two CCS types, being less burdensome on the efficiency (~2.3 percentage points better), having lower capital cost (\$600/kW lower than sweet-shift and \$2700/kW lower than post-combustion), and finally having lower CoE (2 cents/kW-hr cheaper than sweet-shift and 6 cents/kW-hr cheaper than post-combustion.) Fig. 3 shows the difference in emissions output between all three types of CCS for subcritical cycles, Fig. 4 shows the difference in cost between post-combustion and sour-shift pre-combustion CCS, and finally, Fig. 5 shows the difference in efficiency between the baseline and post-combustion CCS.

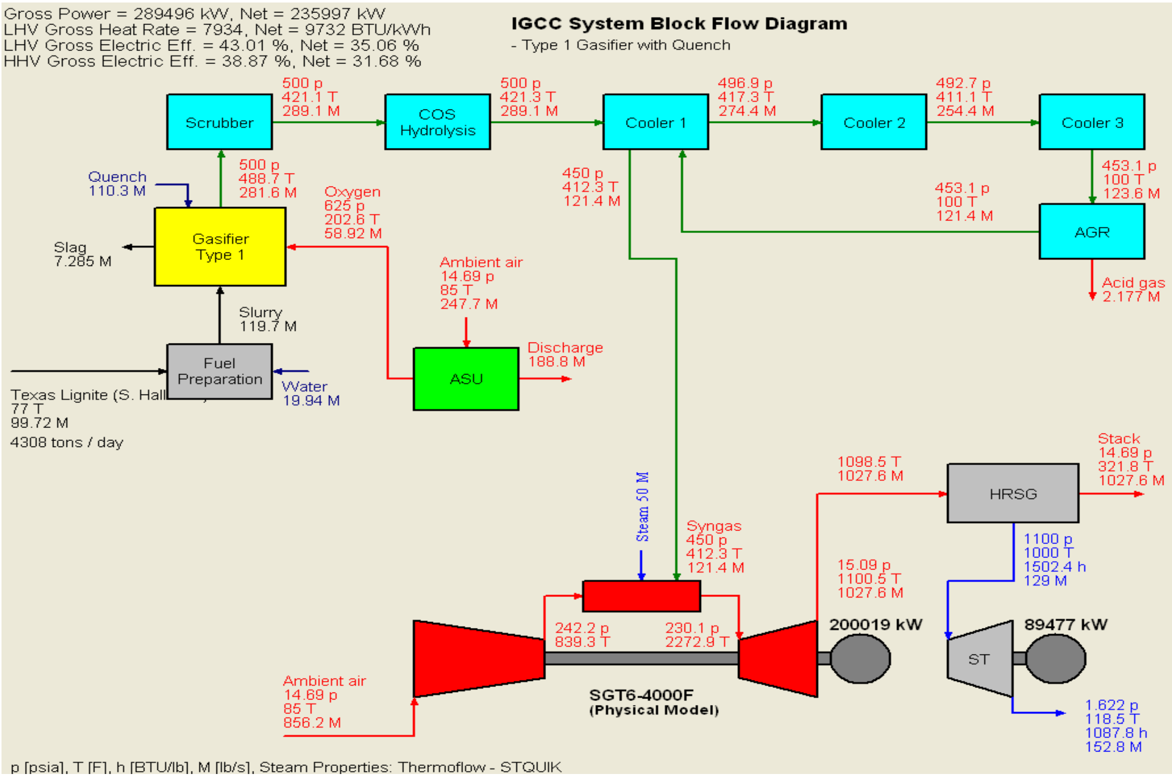

Figure 1 IGCC overall plant layout with subcritical steam cycle

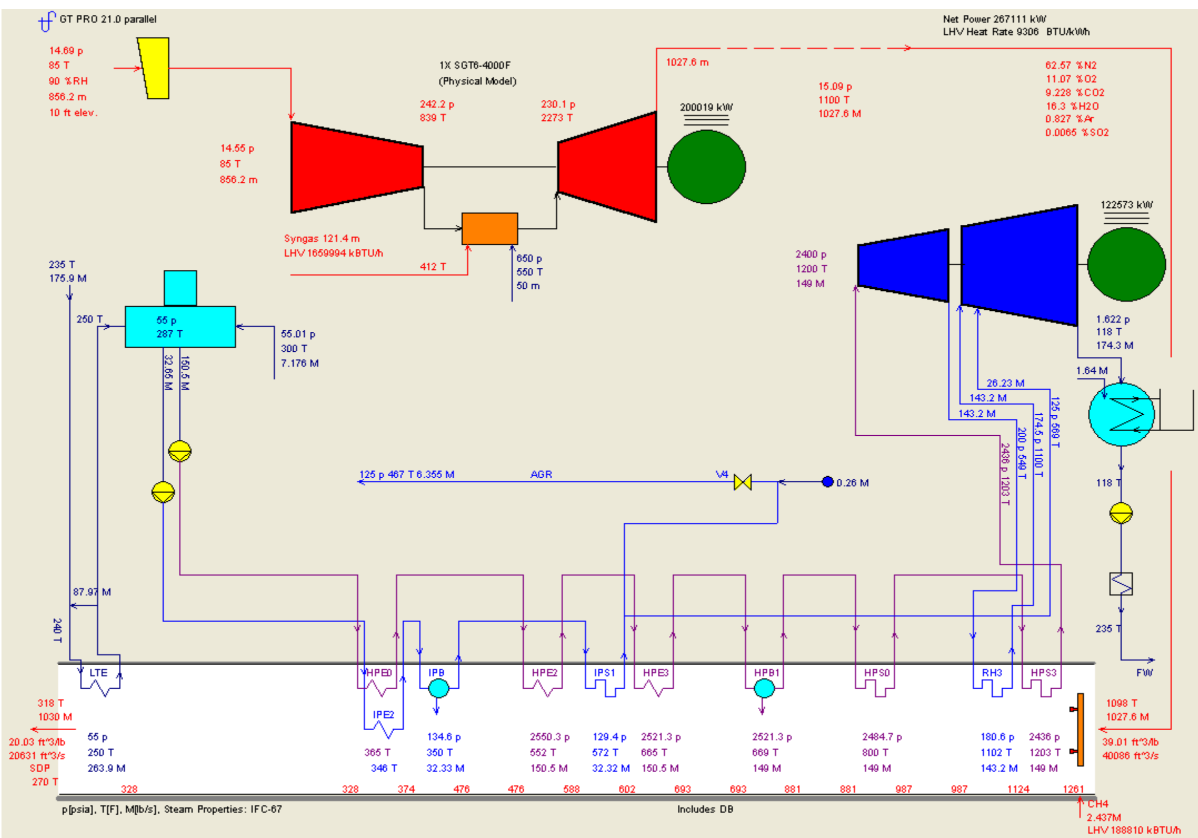

Figure 2 Combined cycle power block design with supercritical steam cycle

Table 1 Supercritical vs. Subcritical: Baseline

Biomass/ Coal Ratio	0%	10%	30%	50%
Subcritical Plants				
Auxiliary Losses (kW)	53,499	52,451	55,913	59,277
Total Net Power (kW)	**235,997**	**237,356**	**234,296**	**231,291**
Gross Efficiency (LHV)	43.01	43.59	43.96	44.31
Net Efficiency (LHV)	**35.06**	**35.70**	**35.49**	**35.27**
Total capital cost (million $)	1,029.8	926.74	911.62	897.44
Capital Cost ($/kW)	**4,363**	**3,904**	**3,891**	**3,880**
CoE ($/kW-hr)	**0.1008**	**0.0979**	**0.1084**	**0.119**
Supercritical Plants				
Auxiliary Losses (kW)	55,481	54,413	57,873	61,235
Total Net Power (kW)	**267,111**	**268,207**	**265,090**	**262,043**
Gross Efficiency (LHV)	44.29	44.84	45.18	45.52
Net Efficiency (LHV)	**36.67**	**37.28**	**37.08**	**36.89**
Total capital cost (million $)	1,087.6	983.83	970.95	956.03
Capital Cost ($/kW)	**4,072**	**3,668**	**3,663**	**3,648**
CoE ($/kW-hr)	**0.0972**	**0.0947**	**0.1041**	**0.1133**

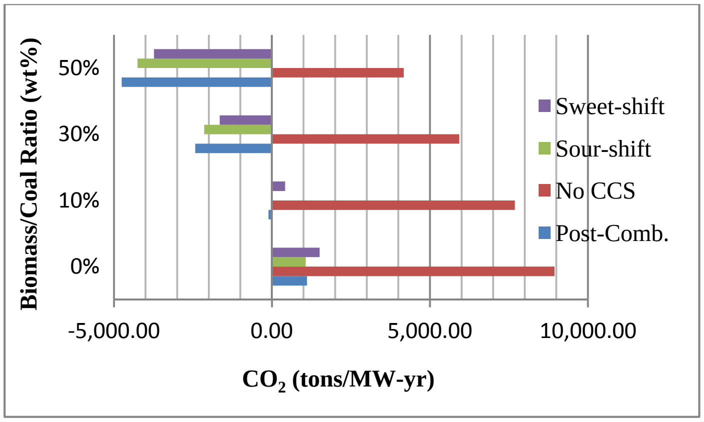

Figure 3 Plant emissions

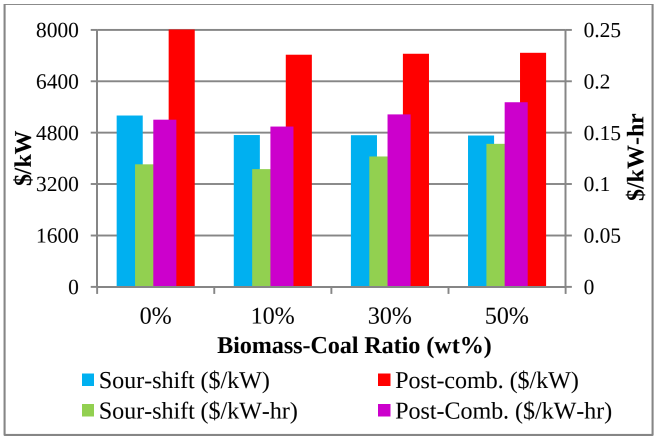

Figure 4 Sour-shift vs. post-combustion economics

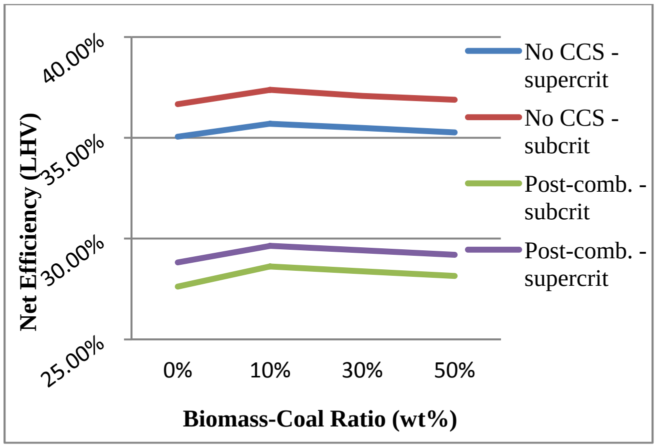

Figure 5 Post-combustion vs. baseline efficiency

Investigation of the Performance of a Syngas Quench Cooling Design and Water-Gas Shift Modeling in Coal Gasification in an Entrained-Flow Gasifier

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Syngas coming out of a gasifier is usually very hot. Cooling is necessary to allow this syngas to be transported without damaging downstream piping or equipment. Furthermore, the existing cold syngas cleaning technology also requires that the syngas temperature to be reduced below 600^{o}F. Direct water quenching of syngas is one of the cooling schemes that can not only provide the necessary cooling, but also help to drive the water-gas shift (WGS) reaction to convert steam and carbon monoxide to carbon dioxide and hydrogen, which is an important process for systems implementing carbon capture and sequestration (CCS). To assist designing an adequate syngas quench cooling section, this study has employed computational fluid dynamics (CFD) to investigate the performance of a preliminary design of a water quench system in a downdraft entrained flow coal gasifier. The preliminary quench system design consists of a primary water curtain section located in the main entrance of the quench section and a secondary water spray section distributed in the outer annular passage with a counter-flow arrangement. The bottom water bath level can be adjusted to change the syngas's local speed over the water surface to fine-tune the WGS reaction without using more sprayed water. The main goal of this study is to use the experimental results to calibrate the CFD model, especially the WGS reaction model, and then to use the calibrated model to help design different water spray strategies to achieve the targeted temperature and syngas composition. The result shows that three different reaction rates (Jones' rate under a catalytic condition, Wade's rate, and Sato's rate under a non-catalytic condition) are all too fast when comparing the CFD results against the experimental data. The exponential constant value (A) of each reaction rate is therefore adjusted to match the experiment data within 2 percentage points (or 6%) in both CO conversion rate and H_2 generation. The effect of the injection locations (primary vs. secondary) on WGS is marginal. Both locations results in 16% CO conversion rate. Spraying water in the primary location only provides a marginal advantage: an increase of 4% in H_2 production, 3% in HHV value, and 30K in temperature. Using water bath level to fine-tune the WGS reaction is workable, although the effect is also marginal. When the water level gap decreases from 1050mm to 700 mm, the CO conversion rate decreases 7 percentage points (or 35%) from 20% to 13%, and the syngas outlet temperature decreases by 20K (from 891 K to 871 K.) Beyond the gap of 1050mm, the effect of the water bath level is not noticeable.

Since three different WGS reaction rates were found too fast when comparing CFD results against the experimental data from the syngas quench system, the other objective of this study is to focused on reviewing the published WGS reaction rates with and without the presence of catalysts, followed by calibrating the WGS reaction rate to match the experimental data taken from the Japanese air-blown CRIEPI research gasifier. The 3-D Navier-Stokes equations and nine species transport equations are solved with seven global gasification reactions (three heterogeneous and four homogeneous,) and a two-step thermal cracking model for volatiles. The Chemical Percolation Devolatilization (CPD) model is used for the devolatilization process. Finite rates are used for the heterogeneous solid-to-gas reactions. Both finite rate and eddy-breakup combustion models are considered for each homogeneous reaction with the smaller of the two rates being used. Three different cases with three different finite rates for the WGS reaction (Jones's rate under catalytic conditions and Wade's and Sato's rates under non-catalytic conditions) are conducted. The result shows that the three originally published rates are all too fast and overpredict the experimental WGS reaction rate. The pre-exponential rate constant value (A) of each reaction rate is therefore adjusted to match the experimental data. The results show that all three WGS reaction rates can match the experimental data reasonably well by reducing the value of the pre-exponential rate constant, A. The exit temperature can be matched within 2% (20K). The mole fractions of CO and H_2O can be matched fairly well within 4 percentage points (or 10%); however, the simulated H_2 mole fractions are always 7-9 percentage points (or about 40%) higher than the experimental data. The calibrated reaction rates are consistent with those obtained earlier from quench section data.

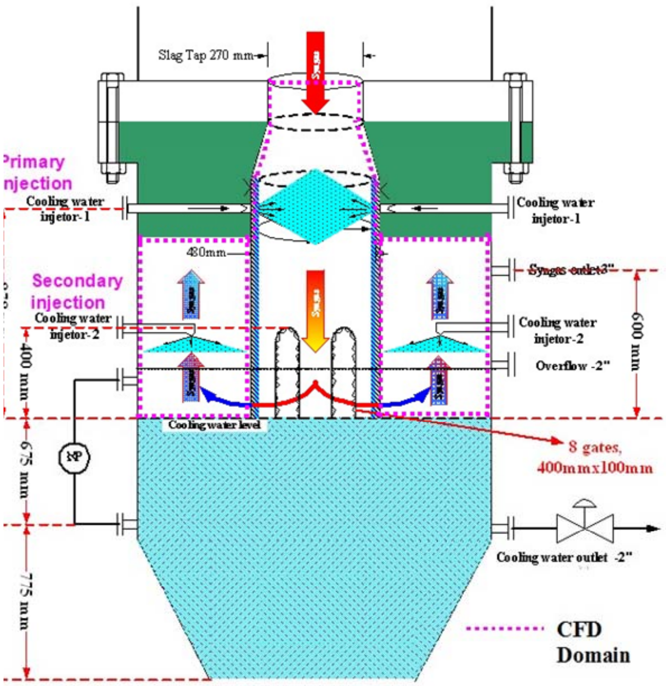

Fig. 1 Gasifier's quench section showing locations of water injections: primary at the inlet and secondary in the outer annular.

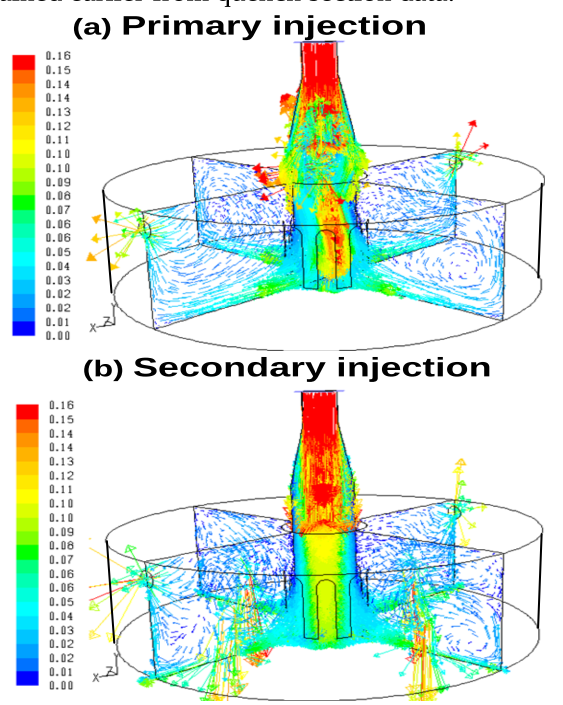

Fig. 2 Velocity vector fields on two selected planes for primary and secondary injection cases, respectively

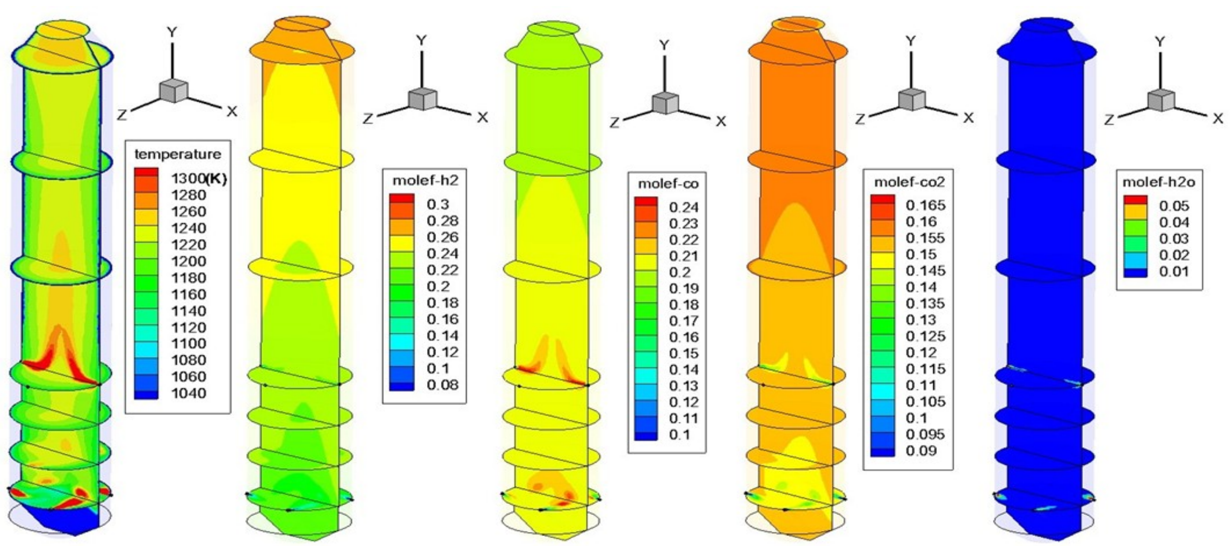

Fig. 3 Gas temperature and species mole fraction distributions for using the Jones's rate in CRIEPI research scale coal gasifier. (A=2.75x1010 E=8.38x107 J/kmol)