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TECHNICAL REPORT

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"FEASIBILITY STUDY FOR AN ADVANCED COAL FIRED HEAT EXCHANGER/GAS
TURBINE TOPPING CYCLE FOR A HIGH EFFICIENCY POWER PLANT"

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1. EXECUTIVE SUMMARY

The overall objective of this project is to prove the feasibility of AFR's concepts for a high efficiency coal-fired generating plant using the REACH/Exchanger concept to power an externally fired gas turbine. It will provide a design of an advanced technology furnace/heat exchanger combination in which a ceramic heat exchanger is aerodynamically protected from the corrosive particle laden coal combustion products. The heat exchanger is fired by radiative and convective heat transfer from a moderately clean fuel stream and by radiative heat transfer from the flame of a much larger uncleaned fuel stream. The fluid mechanics in the furnace/heat exchanger are controlled so that the flow of the combustion products, from the moderately clean fuel stream, sweeps past the heat exchanger to prevent the contact of coal particles with the heat exchanger material.

Task 1 - Project Work Plan

This task was completed.

Task 2 - 2-D Model Calculations

A special firing scheme with two secondary air injection ports was modeled. This case achieved significant aerodynamic cleaning and the concept of modifying the firing scheme to control the turbulent particle dispersion in the HITAF/REACH-Exchanger reactor was verified.

Task 3 - 3-D Model Calculations

The particle dispersion with the two secondary injection case proposed in Task 2 was modeled. Results compared favorably to the cases run so far and minimum particle fouling was seen in this case. A three dimensional case was also modeled in this reporting period and the results confirmed the two dimensional calculation.

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2. INTRODUCTION

Significant improvements in efficiency for the conversion of coal into electricity can be achieved by cycles which employ a high temperature recuperative gas turbine topping cycle. The objective of this project is the development of a new and proprietary concept for an externally fired gas turbine system. The chief advantage of this route is that the potential problems caused by the coal's inorganic constituents are diverted from the high temperature rotating parts of the gas turbine to the high temperature stationary parts of a heat exchanger. The key technology issue is, then, the development of methods to fire a high temperature heat exchanger with coal in such a way that the potential damage from the inorganic constituents is minimized.

The solution offered in this project is the design of a High Temperature Advanced Furnace (HITAF) with a Radiatively Enhanced, Aerodynamically Cleaned Heat-Exchanger (REACH-Exchanger). The REACH-Exchanger is fired by radiative and convective heat transfer from a moderately clean fuel stream and radiative heat transfer from the flame of a much larger uncleaned fuel stream. The approach is to utilize the best ceramic technology available for high temperature parts of the REACH-Exchanger and to shield the high temperature surfaces from interaction with coal minerals by employing clean combustion gases that sweep the tube surface exposed to the coal flame.

The proposed base case REACH-Exchanger configuration and HITAF is shown schematically in Figure 2-1. The HITAF contains several burner/REACH-Exchanger units. The REACH-Exchanger receives air preheated to 1280°F elsewhere in the furnace using a metal heat exchanger. The temperature is raised to 2111°F in the REACH-Exchanger and further heated in an in-duct burner to 2530°F before introduction to the gas turbine.

In the proposed system, 80% of the energy to the REACH-Exchanger is supplied by radiation. The clean stream can be natural gas (base cycle) or volatile products of pyrolysis, low BTU gas from coal carbonization, or products of coal gasification (evolutionary cycle). The uncleaned stream can be coal or char.

Preliminary calculations and assessments indicate that:

- the proposed REACH-Exchanger can be incorporated into a proven furnace design for low reactivity fuels
- the HITAF/REACH-Exchanger can be employed in a cycle similar to that presented in PRDA No. DE-RA22-90PC90159 with at least 47.3% efficiency generation of electricity
- the plant can meet stringent emissions goals using available technologies
- the proposed plant would have a cost of electricity at least 11% lower than that of a conventional pulverized coal-fired plant with scrubber
- development and commercialization of the proposed plant appears accomplishable in ten years

There are two critical technology areas to be addressed in this project.

Figure 2-1. HITAF/REACH-Exchanger. a) Burner REACH-Exchanger Unit; b) HITAF Showing Two REACH-Exchanger Burner Units.

1. HITAF/REACH-Exchanger Radiative Heat Transfer - A design will be developed which allows sufficient radiation to the heat exchanger from the uncleaned stream and allows the heat exchanging surfaces to be kept clean using the flow of combustion products from the clean stream. Initial calculations show that the configuration of Figure 2.1 has the required low turbulence flows to keep the surface clean and allows sufficient radiative heat transfer from the coal flames in the REACH-Exchanger while meeting the overall requirement for energy balance and burnout in the HITAF. This is being tested using a comprehensive computer model for coal combustion and heat transfer (PCGC-2).

2. 3-D CFD Modeling - To test the ability to keep the heat exchanger surface clean by aerodynamics, we have applied an advanced 3-D Computational Fluid Dynamics (CFD) model which will include particles but not coal combustion.

The overall objective of this project is to prove the feasibility of the designs and concepts for a high efficiency coal fired generating plant using the REACH-Exchanger concept to power an externally fired gas turbine.

The project is being carried out in three tasks with the following specific goals:

Task 1 - Project Work Plan Preparation - To develop a research plan based on the program objectives to address the critical issues and answer the key questions.

Task 2 - Two-Dimensional Computations - To demonstrate the heat exchange in the proposed design using a 2-dimensional CFD comprehensive (PCGC-2) and high temperature emissivity measurements.

Task 3 - Three-Dimensional Computations - To demonstrate the aerodynamic cleaning of the heat exchanger.

3. TECHNICAL PROGRESS

3.1. Task 1 - Project Work Plan Preparation

Objective

To develop a research plan based on the program objectives to address the critical issues and answer the key questions.

Summary

This task was completed.

3.2. Task 2 - Two-Dimensional Computations

Objective

To demonstrate the heat exchange in the proposed design using a 2-dimensional CFD comprehensive (PCGC-2) and high temperature emissivity measurements.

Summary

Work during this reporting period continued to test a new firing scheme. The geometry is shown in Figure 3.1 (top view). In this modification, two secondary (secondary I and II) inlets were used. One half of the total secondary air was injected through the secondary I inlet. The diameter of this inlet was reduced from the original design to maintain the same gas velocity. The other half of the total secondary air was fed through the secondary II inlet, which is an annulus about 0.87 meter from the center line of the reactor cylinder. Since the secondary II inlet was placed between the primary coal stream and the heat exchange tubes, it was expected that the combined air flow from the tertiary and secondary II inlets would create an air curtain to prevent particles from hitting the wall. Another benefit expected from this design is a low NO_x emission due to the staggered combustion.

Results of a PCGC-2 simulation of this case show an air flow pattern that had no recirculation zone anywhere in the reactor. Figure 3.2 compares the gas flow patterns of the base case reported previously and this new case, and shows that the new case has a gas flow pattern without any recirculation zone in the reactor, which appears in the base case. It is demonstrated that, with the modified firing scheme, the particle fouling caused by the transport of the background flow can be largely eliminated. Results also show that the inlet modification does not significantly affect the turbulence intensity of the combustion. Hence, the turbulence particle dispersion mechanism seems to be the major mechanism of particle transport in this case. Control of turbulence particle dispersion needs to be improved by modifying both the firing schemes and the reactor geometry.

This concept is shown in Figure 3.3 with a rectangular shaped reactor. When the cleaning air inlets are added, the flame shape will be affected so that less particle turbulence dispersion will be directed toward the heat exchange tubes. Selecting an appropriate shape for the coal conduit can help to achieve the flame shape control.

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Summary

Primary Air and Coal	= 0.39 m
Secondary I Air	= 1.035 m
Secondary II Air	= 1.744 m
Flame	= 1.5 m
U-Tubes	= 2.25 m
Reactor	= 2.75 m

Figure 3.1. HITAF/REACH-Exchange Reactor, Top View.
Cases 8 and 9.

Figure 3.2 Velocity Vector Plot. a) The Base Case; b) Two Secondary Injection Case.

Figure 3.3. Top Views of a Rectangular REACH Reactor, Showing the Effect of Cleaning Air on the Shape of the Flame. a) Without the Cleaning Air; b) with the Cleaning Air.

3.3. Task 3 - Three-Dimensional Computations

Objective

To demonstrate the aerodynamic cleaning.

Summary

During this reporting period work concentrated on running the CELMINT computer code on the new REACH design described in Task 2. The temperature field was obtained from the PCGC-2 computer code and used as input for the CELMINT code. The gaseous phase flow field was obtained in 800 time steps. The flow patterns obtained were considerably different from those obtained in the previously run cases. Because of the splitting off of a portion of the secondary air and injecting this split-off portion of the secondary air at a larger radius, the large recirculation zone normally obtained on the outer wall was not observed. As expected two small recirculation zones were formed in the base regions, but these zones are small and have little effect on the flow pattern. Figure 3.4 shows the particle paths obtained with the CELMINT code for three particle sizes. For all the cases run to date with no side wall injection these results are the most promising. For the 10 micron case, one particle does penetrate the region of the heat exchanger.

Also performed during this reporting period was running the CELMINT computer code for the three-dimensional tertiary flow calculation previously run for the axisymmetric tertiary flow case. The flow conditions were the same as for the previously reported axisymmetric case. The inflow consists of a primary coal/air flow, a secondary air flow and a tertiary methane/air flow. The initial condition was taken from the converged axisymmetric case. For the three-dimensional case, a heat transfer tube was inserted in the flow device. The streamwise and cross plane grid are shown in Figure 3.5. Because the heat transfer tubes are symmetrically placed, the flow pattern repeats every 6. degrees as is shown by the cross plane grid. The streamwise grid consists of 100 streamwise stations and 50 radial stations. In the circumferential direction 25 grid points were used. Convergence was obtained in 300 time steps.

Results of the calculation are shown in Figures 3.6 to 3.8. In Figure 3.6 the velocity vectors are shown in the injection region. The flow pattern shows the effect of the heat transfer tube. The down flow from the tertiary injection cannot be seen. In contrast, in Figure 3.7 the downflow is evident. This effect was seen in the axisymmetric case as would be expected. Because the size of the heat transfer tube is a small percentage of the cross section of the combustor, the overall effect on the flow pattern is minimal. This can be seen in Figure 3.8, the pressure contours. Very little difference is seen between the streamwise pressure contours located over the center of the blade and in the region between the blades. To some extent the basic flow patterns differ little from the axisymmetric case. This is probably due to the large number of heat transfer blades and the fact that they prevent the circumferential velocity component from becoming large.

PARTICLE PATHS CASE – MODIFIED

(two secondary injections)

10 microns

30 microns

100 microns

Figure 3.4. Particle Paths – Modified Secondary Air Flow (two secondary injections).

STREAMWISE & CROSS-PLANE GRID

Tertiary Flow

Figure 3.5. Streamwise & Cross-Plane Grid (tertiary flow).

VELOCITY VECTOR PLOTS

Tertiary Flow

Center of Blade

Figure 3.6. Velocity Vector Plots - Center of Blade (tertiary flow).

VELOCITY VECTOR PLOTS Tertiary Flow Between Blades

Closeup

Figure 3.7. Velocity Vector Plots - Between Blades (tertiary flow).

PRESSURE CONTOURS

Tertiary Flow

Center of Blade

Between Blades

Figure 3.8. Pressure Contours (tertiary flow).

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