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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. In principle, 35% of the energy will be provided by the former and 65% by the latter. 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 uncleaned stream.

Task 1 - Project Work Plan

A detailed management plan was written and submitted to the COTR for approval.

Task 2 - 2-D Model Calculations

Based on the proposed requirements on the REACH/Exchanger reactor, a preliminary design of the reactor was finished. It includes the reactor geometry, coal and gas flow rate and feeding scheme, inlet configuration and the placement of the heat exchanger tubes.

Task 3 - 3-D Model Calculations

No work was performed.

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 proposal 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 Fig. 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

Figure1. HITAF/REACH-Exchanger. a) Burner REACH-Exchanger Unit; b) HITAF Showing Two REACH-Exchanger Burner Units.

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

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 Fig. 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 will be 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 propose to apply 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

Meetings were held at AFR with personnel from SRA. Information and status of preparing 2-D and 3-D calculations were exchanged. Data interaction and exchange between 2-D and 3-D calculations were discussed. Also discussed was the management plan of the contract. A detailed management plan was submitted to the COTR.

Access to the Cray Y-Mp supercomputer was obtained from SCEE at UNLV for the full scale 3-D calculations.

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

The REACH/Exchanger reactor design was completed during this reporting period as scheduled.

Computational REACH/Exchanger Design

Basic Requirement - As required in Section 5 of the proposal, the proposed plant is assumed to generate 100 MW of electricity at 47.4% efficiency by burning 719×10^6 BTU/hr (211 MW) of fuel. The plant is assumed to have 10 burner REACH/Exchanger units, each burning 3,954 lbs/hr of coal and 503 lbs/hr of natural gas. The REACH/Exchanger raises the working fluid temperature from 1280°F to 2111°F. An additional 503 lbs/hr of natural gas are fired in an in-duct burner to raise the working fluid temperature to 2530°F so that a turbine inlet temperature of 2300°F is achieved after mixing with the first stage cooling air.

Based on the plant with 10 REACH/Exchanger reactor units, the energy and materials balances are:

1. A total of 10.06×10^3 lbs/hr of natural gas is fired, 5030 lbs/hr in the ten heat exchangers and 5030 lbs/hr in the in-duct burner.
2. The high temperature ceramic heat exchanger raises the temperature of 1.02×10^6 lbs/hr of air working fluid from 1280°F to 2111°F. This requires

239 x 10⁶ BTU/hr (70 MW) of power.

3. The natural gas in the heat exchangers (5.3 x 10³ lbs/hr of natural gas plus 106 x 10³ lbs/hr of air) transfers 48 x 10⁶ BTU/hr (14.1 MW) of power to the heat exchanger as its temperature goes from 3428°F to 2000°F.
4. The coal combustion products (502 x 10³ lbs/hr) transfer 191 x 10⁶ BTU/hr (56 MW) to the heat exchanger by radiation. The initial energy in the combustion products are 1077 BTU/lbs of combustion products, of which 927 BTU/lb of combustion products comes from the coal and 150 BTU/lb of combustion products comes from the preheated air (750°F). This enthalpy in the combustion products would produce a temperature of 3830°F if there were no losses. The temperature never gets that high because the flame is radiating energy away as the fuel burns. After a loss of 191 x 10⁶ BTU/hr, the combustion stream will be at 2647°F.
5. 5.3 x 10³ lbs/hr of natural gas is fired in the in-duct burner to raise the temperature from 2111°F to 2530°F.

The geometry for the burner/REACH-Exchanger unit requires that the flame deliver 56 MW of radiated energy to the heat exchanger. The net radiation intensity absorbed by the heat exchanger will be

$$R = \sigma \epsilon (T_{\text{flame}}^4 - T_{\text{HE}}^4)$$

where T_{flame} and T_{HE} are the temperatures of the flame and heat exchanger, respectively, and ϵ is the emissivity of the heat exchanger tubes. The emissivity of the flame is assumed to be unity. The geometry of the flame and HE is shown schematically in Fig. 2 with the radiation emitted by both the flame and HE. At the hot end of the heat exchanger $T_{\text{flame}} = 3200^\circ\text{F}$ and $T_{\text{HE}} = 2580^\circ\text{F}$, where we assume a 470°F difference between the outside ceramic temperature and the working fluid gas temperature. Only a fraction ϵ of the radiation incident on the heat exchanger is absorbed by it, giving a net gain of

$$R = 40 \text{ W/cm}^2$$

assuming an emissivity of 0.8 for the heat exchanger surface (see below).

At the low temperature end of the heat exchanger

$$R = 24 \text{ W/cm}^2,$$

assuming the average flame temperature seen by the surface is 2647°F and the ceramic surface temperature is 2000°F. This assumes a 720°F difference between the outside ceramic temperature and the working fluid temperature. The radiative heat exchanging from the flame to the ceramic, is then,

$$R_{\text{avg}} = 32 \text{ W/cm}^2.$$

An area of 1.75 x 10⁶ cm² (175 m²) will thus be required to supply 56 MW to the heat exchanger. The flame radiation can be distributed in ten burners each with 17.5 m² of each

Figure 2 High Temperature Heat Exchanger and In-Duct Burner Radiative Heat Transfer.

burner unit. The Westinghouse base case would require 235 m² to deliver 66 MW of radiated power to the heat exchanger.

Computational Reactor

Based on the above calculation, the reactor is a 9 m tall cylinder with 2.75 m ID as illustrated in Fig. 3. Fuel is fired from the top of the reactor in a down fire configuration. Pulverized coal particles are fed from the primary tube in the center top position of the reactor (Fig. 1). The secondary inlet is an annular pipe around the primary to supply oxidant (air). The coal feed rate is 3954 lbs/hr per burner and the total air feed rate in the primary and the secondary is 46,300 lbs/hr per burner. The air temperature is 753°F. Fifteen percent of the total air fed is in the primary and 85% is in the secondary. To prevent back fire, the primary gas velocity has to be higher than 50 ft/sec. This requires that the ID of the primary be smaller than 0.37 m. The secondary tube ID is 0.85 m to give approximately the same gas velocity as in the primary.

We will use 56 ceramic exchange tubes placed at a circumference of 1.125 meters from the center line of the reactor cylinder. The outside diameter of the tubes is 0.0635 m. This gives a total of 100.5 m² radiation absorption surface, half of which is facing the flame.

The relative positions of the primary and secondary inlets, the tubes, and the flame are given in Fig. 4. It is assumed that the coal is burned stoichiometrically with sufficient air so that a flame of the optimal thickness (1.5 m) can be achieved.

The tertiary inlet supplies the nature gas and air at rates of 503 lbs/hr and 10.6 x 10³ lbs/hr, respectively. The position and the feeding scheme are to be investigated to obtain the optimum dynamic cleaning effect.

The premixture of the primary air and the coal will lower the air temperature while increasing the coal temperature according to the following:

$$6950 (T - 673) C_p(\text{air}) + 3954 (T - 300) C_p(\text{coal}) = 0$$

where T is the air and coal temperature after the mixture, C_p(air) and C_p(coal) are the specific heat of air and coal, respectively. Before mixing the air temperature is 673 K (750°F) and coal temperature is 300 K (room temperature). Now C_p(air) = 1.065 and C_p(coal) = 1.548 so T = 504 K.

The summary of the design is provided in Table 1.

3.3. Task 3 - Three-Dimensional Computations

Objective

To demonstrate the aerodynamic cleaning of the heat exchanger.

Summary

The subcontract for Scientific Research Associates, Inc. was completed and signed.

Figure 3. The REACH-Exchange Reactor, Side-view. The Positions of the Heat Exchanger Tubes are not Shown.

Summary

Primary Air and Coal	= 0.35 m
Secondary Air	= 0.85 m
Flame	= 1.5 m
U-Tubes	= 2.25 m
Reactor	= 2.75 m

Figure 4. REACH-Exchange Reactor, Top View.

TABLE 1

Geometry and Inlets of REACH/Exchanger for Modeling

Geometry	
Primary tube diameter, m	0.35
Secondary tube diameter, m	0.85
Chamber diameter, m	2.75
Chamber length, m	9.14
Feed rates	
Primary gas, kg/s (lb/hr)	0.875 (6.95E3)
Secondary gas, kg/s (lb/hr)	4.96 (3.935E4)
Primary + secondary, kg/s (lb/hr)	5.83 (4.63E4)
Tertiary gas	
CH ₄ , kg/s (lb/hr)	0.0668 (0.503E3)
Air, kg/s (lb/hr)	1.336 (10.6E3)
Coal in primary, kg/s (lb/hr)	0.497 (3.95E3)
Inlet properties	
Primary swirl number	0.0
Primary turbulent intensity	
Primary temperature, k	504
Primary mole fraction	
N ₂	0.79
O ₂	0.21
Secondary swirl number	
Secondary turbulent intensity	
Secondary temperature, k (°F)	673 (750)
Secondary mole fraction	
N ₂	0.79
O ₂	0.21
Reactor parameters	
Reactor pressure, N/m ²	1.013E5
Side wall temperature, K (°F)	1416 (2580)
Particle parameters	
Particle solid density, kg/m ³	1300
Mass mean particle diameter, m	7E-5
Heat exchange tubes,	
Outside Diameter, m	56
Distance from center line, m	0.0635
	1.125

END

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