14D
ADVANCED
FUEL
RESEARCH

P. O. Box 380379
East Hartford, Connecticut 06138-0379
Telephone (203) 528-9806
Fax (203) 528-0648

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

Prepared by

Peter R. Solomon
Yuxin Zhao
and
Richard C. Buggeln
Stephen J. Shamroth

ADVANCED FUEL RESEARCH, INC.
87 Church Street
East Hartford, CT 06108

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**"FEASIBILITY STUDY FOR AN ADVANCED COAL FIRED HEAT EXCHANGER/GAS
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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 later. 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

This task was completed.

Task 2 - 2-D Model Calculations

The computational REACH reactor was modeled with PCGC-2. The reactor geometry, inlet flow rates and configurations were investigated via modeling in order to get an optimum operation condition, with which a thorough coal and gas mixture and a required coal particle dispersion can both be achieved. This is to ensure the efficiencies of both coal combustion and aerodynamic cleaning.

Task 3 - 3-D Model Calculations

The aerodynamic cleaning effect of the tertiary air injection was modeled with CELMINT. Various injection schemes investigated show the dramatic impact of the tertiary air and the injection positions on the overall air flow pattern in the reactor which is one of the major influencing factors on the particle dispersion. It is clearly demonstrated that an optimum tertiary injection scheme with a reasonable flow rate is able to keep the heat exchange tubes from particle fouling.

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.

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.

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.

TEMPERATURE CONTOURS

Figure 1 Temperature contours of Case 1.

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

Based on the design of the computational REACH reactor completed during the preceding reporting quarter, PCGC-2 was used to model this reactor with different operation conditions. The computational grid, inlet configurations and diameters were varied in order to get an optimum operation condition, with which complete coal and gas mixing and a required coal particle dispersion can both be achieved. This is to ensure the efficiencies of both coal combustion and aerodynamic cleaning.

A summary of operation conditions investigated is presented in Table 1. Case 1 was the base case that was given in the preceding quarterly report. The calculated gas temperature contour is given in Figure 1. After examining the results, it appears that the primary air velocity is too high. The coal combustion takes place mostly in the region down in the bottom of the reactor. Thus, because it requires a period of time for thorough coal/oxidant(air) mixing before complete combustion can proceed, the high gas velocity has carried the coal particle cloud down to the bottom. To correct this problem, the tube inlet diameters were then adjusted in order to enhance the mixture.

The diameters of both the primary and the secondary inlets were enlarged, it was hoped that the resulting reductions in the inlet velocities would provide a longer coal particle residence time and so improve the mixture. The adjustments are given in Table 1 (Case 2). Starting from Case 2, the tertiary CH_4 /air combustion stream is included in the computation. This stream is fed in from a large annulus on the top of the reactor and in the vicinity of the wall. The new reactor with the tertiary air is displayed in Figure 2.

Figure 3 displays the temperature contours of this case. It appeared that the reduction in the primary and the secondary air velocities did not help much in lifting the combustion zone to the top of the reactor. Most of the coal particles still burn in the bottom area. The overall

Summary

Primary Air and Coal	= 0.39 m
Secondary Air	= 1.20 m
Flame	= 1.5 m
U-Tubes	= 2.25 m
Reactor	= 2.75 m

Figure 2. REACH-Exchange Reactor, Top View.

CONTOUR LEVELS

600.0000
650.0000
700.0000
750.0000
800.0000
850.0000
900.0000
950.0000
1000.000
1050.000
1100.000
1150.000
1200.000
1250.000
1300.000
1350.000
1400.000
1450.000
1500.000
1550.000
1600.000
1650.000
1700.000
1750.000
1800.000
1850.000
1900.000
1950.000
2000.000
2050.000
2100.000
2150.000

Figure 3. Temperature Contours, Case 2.

burnout of the coal was just 82%, compared to 88% in Case 1. The reduction of the burnout is believed due to the decreases in the coal/oxidant mixing because of the larger primary tube diameter in Case 2. Also the decrease in velocity may decrease the turbulent mixing. Modifications were needed to increase the mixing.

The effect of tertiary air, however, was very evident in that it swept the hot combustion zone away from the wall in the bottom of the reactor. This effect can be noticed by comparing the temperature contours of Figure 3 with that of Figure 1.

A particle stochastic turbulence dispersion model was developed. It uses the gas field information provided by PCGC-2 to predict the particle dispersion in the reactor. A comparison of the particle dispersions of Case 1 and 2 given in Figure 4 clearly demonstrated the effectiveness of the tertiary stream in sweeping particles away from the heat exchanger area (near the wall, see Figure 2). For both cases in Figure 4, the data was plotted based on a calculation of 125 particles. With Case 1, there was a gas recirculating zone in the top corners of the reactor, which caused large scale particle recirculating movement in the same fashion. The gas recirculating zone was suppressed effectively in Case 2 by adding the tertiary air, and therefore the coal particles were kept away from the wall. The effect of tertiary air on the overall flow pattern was further confirmed by the calculations in Task 3. The predictions showed that the tertiary air reduced the particle collisions with the wall most effectively in the top half of the reactor. Therefore, it increased the need to move the combustion zone up.

Cases 3, 4 and 5 were studied to improve the mixing by adding swirl in the secondary. Case 3 was featured with a quarl region around the secondary inlet (divergent), but the computation convergence was not achieved for this case. The difficulty in converging the gas field might come from the special geometry and the swirl.

Cases 4 and 5 had swirl numbers of 0.5 and 1.0, respectively. With swirl 0.5, Case 4 did not accomplish any improvement over Case 2 in terms of the burnout (83%). But comparing its temperature contours (Figure 5) with those of Case 2 shows more combustion in the top section of the reactor.

With swirl number of 1.0 in Case 5, the overall burnout was increased to 90%. Its temperature contours are presented in Figure 6, which shows the most stabilized flame and complete combustion among the five cases. However, the increasing swirl created a large tangential stirring force, which caused an unfavorable particle dispersion pattern.

The particle dispersion patterns of Cases 4 and 5 are displayed in Figure 7. Obviously, the tangential stirring air caused a larger amount of particle dispersion, which should be avoided. Further modification will then focus on the improvement of the mixing and so the combustion efficiency by using non-swirl firing systems. Focus will be on the development of an optimum air flow pattern that provides: 1) a stable flame, 2) highly efficient combustion, and 3) low particle fouling on the heat exchange tubes. Modeling in this direction is in progress.

Case 2

Case 1

Figure 4. Particle dispersions of Cases 1 and 2.

CONTOUR LEVELS

650.0000
700.0000
750.0000
800.0000
850.0000
900.0000
950.0000
1000.000
1050.000
1100.000
1150.000
1200.000
1250.000
1300.000
1350.000
1400.000
1450.000
1500.000

1600.000
1650.000
1700.000
1750.000
1800.000
1850.000
1900.000
1950.000
2000.000
2050.000
2100.000
2150.000

Figure 5. Temperature contours of case 4.

CONTOUR LEVELS

600.0000
650.0000
700.0000
750.0000
800.0000
850.0000
900.0000
950.0000
1000.0000
1050.0000
1100.0000
1150.0000
1200.0000
1250.0000
1300.0000
1350.0000
1400.0000
1450.0000
1500.0000
1550.0000

1600.0000
1700.0000
1750.0000
1800.0000
1850.0000
1900.0000
1950.0000
2000.0000
2050.0000
2100.0000
2150.0000
2200.0000
2250.0000

Figure 6. Temperature Contours of Case 5.

Case 4

Case 5

Figure 7. Particle dispersions of Cases 4 and 5.

TABLE 1

Operation conditions modeled with PCGC-2 in this reporting period

	Case 1	Case 2	Case 3	Case 4	Case 5
Primary diameter, M	0.35	0.39	0.39	0.39	0.39
Secondary diameter, M	0.85	1.2	1.2	1.2	1.2
Tertiary air	No	Yes	Yes	Yes	Yes
Swirl number	-	-	0.5	0.5	1.0
Quarl region	No	No	Yes	No	No

3.3. Task 3 - Three-Dimensional Computations

Objective

To demonstrate the aerodynamic cleaning of the heat exchanger.

Summary

During this reporting period work concentrated on running a series of axisymmetric cases to obtain a first approximation to tertiary methane/air strategies which would be most effective in protecting the heat exchanger in a HITAF/REACH type combustor. Prior to discussing the results obtained to date, it is useful to consider the various physical mechanisms which would cause particle and trace species dispersion. Three major mechanisms are present. The first being convection by the background flow, the second being the particle flow angle on inflow and the third being dispersion of discrete particles by the turbulent component of the background flow. The CELMINT analysis includes all three.

Particles of interest are introduced to the burner at the inflow port or created during the combustion process. For the present study particles are tracked from the inflow port, which is the central coal/air stream along the axis. For the purpose of the present study, it is assumed that upon inflow, the axial velocity is equal to the axial velocity of the background flow. In addition, a radial velocity is assumed such that the flow angle relative to the axis of symmetry is 6° . The turbulence of the continuum background flow was obtained from a solution of the two equation k- ϵ turbulence model. This provided a local turbulence intensity which is input into a statistical algorithm to provide the instantaneous flow leading to particle dispersion by background turbulence. It should be noted that this algorithm adds a fluctuating component to the local background mean flow, allowing the particle to be influenced by the background flow turbulence.

The procedure is based upon a random number generator; however, for each run the generator is always started at the same place, thus making the results deterministic in the sense that for (i) a given background flow and (ii) a given number of inflow particles with prescribed velocity and position the generated particle paths are repeatable. However, if a

new particle is added between two existing particles, the new particle path, in general, will not be confined to the region between the two original particle paths. This is important in interpreting the plots. In addition, due to the random nature there is always a chance that any single particle may follow an unexpected path which does not vary in an orderly manner from paths of initially adjacent particles. The initial radial velocity is expected to be most important for the large particles as it provides the initial particle momentum which is modified with time by the background flow drag force and turbulence. It is less important for small particles since their low mass (i.e., low momentum) makes them come to equilibrium with the background flow more quickly. In contrast, the background turbulence has more influence on the smaller particle. This provides a random, instantaneous flow field which influences the particles via a random drag force and those particles having lower momentum, i.e., the smaller particles, are more subject to these turbulent fluctuations.

The calculations were carried out with a primary stream mass flux of 1.372 kg/sec, a secondary mass flux of 4.96 kg/sec, and a tertiary stream mass flux of 1.4028 kg/sec. Initially, three sets of calculations were performed. The first had no tertiary injection; the second had tertiary injection from an annulus located at the top of the furnace near the outer edge; the third had flow injected from a slit at the outer diameter wall located approximately one-half way along the length of the furnace. Gravity was included in the calculation. The furnace radius was approximately 1.3 m and the length 9.2 m.

Velocity vector plots for the three cases are shown in Figs. 8 - 10, for the overall flow field and a "close-up" of the recirculation zone. In all cases the inflow at the top of the furnace is at the left, the axis of symmetry at the bottom, the outer wall at the top and outflow at the right. The plots have been rotated by 90° from their physical orientation for ease of viewing. Gravity is in the left-to-right direction. The color represents the velocity magnitude as per Table 2.

TABLE 2

COLOR	SPEED (m/sec)
Blue - Aqua	0 - 10
Aqua - Green	10 - 20
Green - Orange	20 - 30
Orange - Red	30 - 40

Figure 8 shows the base case; no tertiary injection. The development of the flow field in the primary and secondary jets mixing with the quiescent flow and the recirculation region are evident. In these plots velocity vectors near the centerline are omitted, as they were large and obscured the rest of the plot. Figure 9 shows the tertiary flow case with injection of the top of the furnace; i.e., the left side of the plot. As seen, the tertiary air is very quickly turned toward the centerline after injection and adds an additional buffer to the original secondary stream buffer around the primary coal/air stream. This should add protection to the flow. Figure 10 shows the flow for side injection, which energizes the flow downstream of the injection hole. This should provide protection in the downstream region.

No Tertiary Flow

Overall

Closeup

Figure 8. Velocity Vector Plots - No Tertiary Flow.

Overall

Closeup

Figure 9. Velocity Vector Plots - Tertiary Flow.

Particle paths were run for particles originating in the primary stream. For each case the paths of the particles at 10 μm , 30 μm and 100 μm were considered. The different colored lines are simply for ease of viewing. In assessing these results it should be noted that twenty-four particles were injected at the inflow port. Their path is changed due to the mean background flow and the turbulence. Twenty-four particles are a relatively small number to demonstrate the effect of turbulence; however, they are sufficient to provide an estimate of the envelope of particle paths and the results should be viewed in this sense. Figure 11 shows results for the base case; no tertiary injection. In assessing the results note that the heat exchanger is to be placed at 80% of the furnace radius. For no tertiary flow, it is clear that the entire range of particles considered presents a problem. The particles would be dangerously close to the heat exchanger at approximately 40% of the length (for 10 μm), 60% (for 30 μm) and 40% (for 100 μm), respectively. Introduction of tertiary injection at the top of the furnace provides the results shown in Fig. 12. The particles become dangerously close at 60% of the length (for 10 μm), 70% of the length (for 30 μm) and 50% of the length (for 100 μm), respectively. Clearly, even this modest amount of tertiary injection is very beneficial. The third case considered, Fig. 13, is that of sidewall injection, where the heat exchanger would be protected for 75%, 83% and 60% of the length. Figures 14 and 15 show the result of a combined injection case, where 1.4028 kg/sec was injected at the top of the furnace and along the side wall. Further improvement is noted. Finally, Figs. 16 and 17 show side injection through two ports, as well as tertiary injection from the top. The total injected mass from the two side ports and one top port was equal to that of the first combined case, Case 4, and further improvement was shown, particularly for the larger particles. In a case not shown, side injection through the downstream port was made normal to the wall; this decreased cleansing effectiveness. These results are summarized in Table 3.

TABLE 3
LENGTHS PROTECTED

Particle Size	Case 1 No Inj	Case 2 Top Inj	Case 3 Side Inj	Case 4 Combined Inj	Case 5 Combined Inj.
10 μm	40%	60%	75%	90%	90%
30 μm	60%	70%	83%	100%	95%
100 μm	40%	50%	60%	70%	80%

These preliminary calculations indicate that even with a modest amount of cleansing air, heat exchange elements can be protected for 70% of the furnace length. In addition, although not shown here, results have been obtained to show the sensitivity of inlet primary stream flow angle and turbulence level. As expected, in general, although anomalies do appear due to the statistical nature, reducing the inlet primary stream flow angle reduces particle spread and increasing turbulence increases primary stream spread.

During the next reporting period work will concentrate on running the full three-dimensional code for the "best" two-dimensional strategy developed.

10 microns

30 microns

100 microns

Figure 11. Particle Paths - No Tertiary Flow.

10 microns

30 microns

100 microns

Figure 12. Particle Paths - No Tertiary Flow.

10 microns

30 microns

100 microns

Figure 13. Particle Paths - Tertiary Flow (side injection).

Overall

Closeup

Figure 14 Velocity Vector Plot (Tertiary Flow (combined injection))

10 microns

30 microns

100 microns

Figure 15. Particle Paths - Tertiary Flow (combined injection).

Overall

Closeup

Figure 16. Velocity Vector Plots - Tertiary Flow with Two Side Injections.

10 microns

30 microns

100 microns

Figure 17. Particle Paths - Tertiary Flow with Two Side Injections.

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