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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period November 1, 1988 – January 31, 1989

By
J. Balsavich, F.E. Becker, and L.A. Smolensky

March 1989

Work Performed Under Contract DE-AC22-87PC79650

Tecogen Inc.
A Subsidiary of Thermo Electron Corporation
Waltham, Massachusetts

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DOE/PC/79650-10

TR4415-043-89

DE-AC22-87PC79650-10

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TABLE OF CONTENTS

2. WORK PERFORMED DURING THE SECOND QUARTER OF THE SECOND PHASE OF THE PROGRAM	2
2.1 IRIS COMBUSTOR LIFE-CYCLE TESTING AND OPTIMIZATION . . .	2
2.2 HEAT EXCHANGER LIFE-CYCLE TESTING AND OPTIMIZATION . .	16
2.3 BAGHOUSE LIFE-CYCLE TESTING AND OPTIMIZATION	16
2.4 FABRICATION OF THE THIRD-GENERATION FURNACE	16
3. SUMMARY STATUS ASSESSMENT AND FORECAST	22

LIST OF ILLUSTRATIONS

2.1	CWS-Fired Residential Combustor	3
2.2	Primary Combustion Chambers with Multiple Air Inlets	4
2.3	Effect of Excess Air on Combustion Efficiency	5
2.4	Upper Combustion Chamber Wall Temperatures vs Time	7
2.5	Upper Combustion Chamber Wall Temperatures vs Time	9
2.6	Upper Combustion Chamber Wall Temperatures vs Time	10
2.7	Upper Combustion Chamber Wall Temperatures vs Time	11
2.8	NO _x Emissions vs Excess Air	13
2.9	Startup Procedure	15
2.10	Heat Transfer in Shell-and-Tube Heat Exchanger	17
2.11	Effect of Fouling in the Heat Exchanger	18
2.12	Particle Size Distribution in the Fly Ash	19
2.13	Cumulative Particle Size Distribution in the Fly Ash	20

1. INTRODUCTION

The objective of the CWS-Fired Residential Warm-Air Heating System program is the development of an economically viable coal-water slurry fueled furnace that is competitive with current oil and natural gas systems. The program consists of two phases: the first phase was completed in July 1988, and the second phase in progress at this time is scheduled for completion in October 1989.

The design concepts developed, including a novel state-of-the-art IRIS (Inertial Reactor with Internal Separation) combustor, enabled the first-phase program objectives to be met. In particular:

- The developed system demonstrated stable operation with dual-fuel capability (atomizer operated with both oil and CWS)
- Response time was less than 5 minutes to full load
- Steady-state efficiency exceeded 80 percent
- Combustion efficiency exceeded 99 percent, and
- Successful operation was achieved with input rates ranging from 60,000 to 240,000 Btu/hr.

The second phase of the program is a logical continuation of the previous phase. However, in contrast to the first phase, which concentrated basically on the development of the individual system components, the second phase of the program focuses on evaluating the interaction between individual components and system design optimization. Serious consideration is also given to life-cycle testing, which is conducted to identify areas where additional development may be needed. This report summarizes the results of the second quarter of Phase II.

During the report period, the life-cycle testing, optimization, and refining of the second-generation furnace continued. In parallel, work continued on the fabrication and assembly of the third-generation furnace. The third-generation furnace is considered the final laboratory prototype and will serve as the basis for a manufacturing prototype.

2. WORK PERFORMED DURING THE SECOND QUARTER OF THE SECOND PHASE OF THE PROGRAM

2.1 IRIS COMBUSTOR LIFE-CYCLE TESTING AND OPTIMIZATION

During this report period, work continued on the life-cycle testing and refining of the second-generation coal-water slurry (CWS) warm-air furnace. Specifically, this quarter's main goal was to finalize the combustor configuration with respect to the size and location of the air inlets in the upper and lower combustion chambers to yield high combustion efficiency and prevent agglomeration of coal on the partitions that separate the chambers.

The combustor was tested as a two-stage unit and as a single-stage unit. In the single-stage unit, the lower air inlet was blocked. Figure 2.1 shows the combustor with single air inlets in each of the primary combustion chambers. The primary combustion chambers were also tested with multiple air inlets arranged as shown in Figure 2.2.

To determine the effect of two-stage combustion on both combustion efficiency and emissions, a series of tests was conducted with excess air as the main independent variable. For this series of tests, the fuel input rate was increased to 125,000 Btu/hr, up from the nominal 100,000 Btu/hr of previous tests. The reason for increasing the input rate was to increase the pressure drop at which the combustor operated. This helped to insure equal air flows through air inlets (A and B in Figure 2.2).

To illustrate combustor performance in the two-stage mode, Figure 2.3 shows combustion efficiency as a function of excess air. Curve 1 in Figure 2.3 characterizes the performance of the combustor with two air inlets (A and B) in the upper primary combustor chamber and a single air inlet (D) in the lower primary chamber (configuration 1; air inlet D in Figure 2.2 was blocked). The second air inlet (B) in the upper chamber was situated 180 degrees from air inlet A and was about 220 degrees counterclockwise from the supersonic CWS atomizer.

For the series of tests characterized by curve 2 in Figure 2.3 (configuration 2), the air inlets in the upper chamber were made slightly narrower than those of the first configuration with multiple air inlets. The purpose of narrowing the gap in the upper precombustor was to allow the upper chamber to run closer to stoichiometric conditions. Also, the lower combustor liner was modified to have two air inlets (C and D) 180 degrees apart from each other to distribute air better in the lower chamber.

For purposes of comparison, combustion efficiencies obtained from single-stage operation are also shown in Figure 2.3 (curve 3). Figure 2.3 shows that the configuration exhibited a combustion efficiency of 99.4 percent when

Figure 2.1 CWS-Fired Residential Combustor

- 1. Water Cooled Wall
- 2. Combustion Air
- 3. Liners with 1/8 in. Insulation from the Air Side
- 4. Upper Horizontal Partition with Central Opening
- 5. Atomizer
- 6. Lower Horizontal Partition with Central Opening
- A, B, C, D - Air Inlets

Figure 2.2 Primary Combustion Chambers with Multiple Air Inlets

Figure 2.3 Effect of Excess Air on Combustion Efficiency

operated with almost 50-percent excess air. It was found that combustion efficiency decreased with excess air for this configuration, dropping to 98 percent at 16.5-percent excess air. When this configuration is compared with configuration 1, configuration 1 exhibits higher combustion efficiencies over a much broader range of excess air.

Based on a comparison between the single- and two-stage modes of combustion, the two-stage mode is capable of achieving higher combustion efficiencies. In addition to achieving higher combustion efficiencies, the two-stage mode maintains these higher efficiencies over a much wider range of excess air levels. Referring to Figure 2.3, the majority of points from between 10- and 40-percent excess air achieved combustion efficiencies in excess of 98 percent. This is quite a contrast from the single-stage mode of operation, in which the combustion efficiency drops from its value of 98.9 percent at 30-percent excess air to 95.6 percent at 11.3-percent excess air. However, the differences between combustion efficiencies for single- and two-stage modes of operation become smaller for higher excess air ratios, and even the single-stage mode of combustion allows 99 percent of combustion efficiency to be achieved if the excess air ratio is about 35 percent.

As stated previously, the optimal configuration for the IRIS combustor is one that exhibits a high combustion efficiency at design point and is not prone to the agglomeration of coal particles on the upper partition. Since the supersonic atomizer introduces CWS droplets into the upper precombustor with considerable momentum, the droplets impact the liner directly across from the atomizer. If the air distribution within the reactor is not correct, a layer of agglomerated coal forms on the wall at this location. The main difficulty associated with this layer of coal on the upper partition and combustor wall is that when the furnace is shut off, there is still fuel capable of burning in the hot furnace. This would require the system fan to remain on for a short period of time after the CWS supply had stopped to insure that the coal layer had burned completely away.

The rate of deposition and erosion of this layer tends to reach some equilibrium thickness for any given test. The best way to detect the presence of this layer as well as its thickness is to monitor the wall temperature directly across from the atomizer as a function of time, and then compare that to the wall temperature away from the zone where the CWS droplets hit the wall. An example of such a trace is shown in Figure 2.4. For this particular trace, the combustor was operated in the first multiple inlet configuration shown in Figure 2.3. It can be seen from the figure that the coal layer on the wall produced a temperature drop of around 600°F compared to what the clean wall operated at. After the test, a layer of coal about 1-inch thick was found on the upper partition and liner. This layer, however, did not decrease the combustion efficiency. Analysis of ash collected in the baghouse for this particular test had a combustion efficiency of 99.3 percent.

Figure 2.4 Upper Combustion Chamber Wall Temperatures vs Time

The problem of coal agglomerating on the upper partition appears to be aggravated by the use of air inlets in both the upper and lower precombustion chambers. As more air is introduced in the lower chamber to obtain two-stage combustion, the top chamber runs closer to stoichiometric conditions, and in some locations in the upper chamber the unit runs fuel rich. With a local deficiency of oxygen in the upper chamber, it becomes difficult to burn off the agglomerated coal particles. In order to alleviate this problem, it was decided to test the IRIS combustion with the lower precombustor air inlet sealed off. This was similar to the previous single-stage combustion tests, so that all the air for combustion had to enter in the upper precombustor. These tests differed from the original single-stage combustion tests in that the size of the upper chamber air inlet was adjusted so that combustion air had to enter at a higher velocity. The location of the inlet could also be adjusted to any location in the upper chamber.

As a first attempt, air inlet A (Figure 2.2) was located about 40 degrees counterclockwise from where the agglomeration typically forms. In this configuration the air inlet was upstream of the agglomeration site to allow the incoming combustion air some distance to be heated before encountering the agglomeration site. The temperature versus time trace for this configuration is shown in Figure 2.5. As Figure 2.5 shows, the temperature difference between the agglomeration site and the clean wall is only about 200°F. After the test, an agglomeration thickness of only about 1/2 inch was found in the upper precombustion chamber. The combustion efficiency for this test was 99.0 percent, based on analysis of ash collected in the baghouse.

The second configuration tested to reduce agglomeration buildup consisted of two air inlets, A and B, in the upper chamber. The first inlet (A) was located 40 degrees counterclockwise from the agglomeration site, the same as in the previous test, and the second air inlet (B) was located 180 degrees counterclockwise from this inlet, approximately 70 degrees upstream of the agglomeration site. The temperature versus time trace for this configuration is shown in Figure 2.6. For this configuration, a coal agglomeration about 1 inch thick was found in the upper precombustor. This indicated that velocity was reduced by having two separate inlets in the upper chamber, which is not as desirable as having a single, high-velocity inlet placed in the upper chamber. The combustion efficiency for this configuration was found to be 98.9 percent based on analysis of ash collected in the baghouse.

In the third configuration tested, a single air inlet approximately 70 degrees upstream of the agglomeration site was tested. The temperature versus time trace for this configuration indicated that the temperature difference between the clean combustor wall and the agglomeration site is very small, as shown in Figure 2.7. After the test, no agglomeration was found in the IRIS combustor. The combustor efficiency of this test was found to be 99.0 percent based on the analysis of ash collected in the baghouse. This combination of

Figure 2.5 Upper Combustion Chamber Wall Temperatures vs Time

Figure 2.6 Upper Combustion Chamber Wall Temperatures vs Time

Figure 2.7 Upper Combustion Chamber Wall Temperatures vs Time

high combustion efficiency along with the lack of agglomeration in the upper precombustor chamber makes this configuration highly desirable.

The emissions of different configuration combustors were analyzed. The effect of two-stage combustion on NO_x emissions is shown in Figure 2.8 (the combustor configuration with two air inlets in the upper chamber and a single air inlet in the lower chamber). For purposes of comparison, single-stage NO_x levels are also shown. It can be seen in Figure 2.8 that there is more scatter associated with the two-stage data than for the previously obtained single-stage data. Also, contrary to what is expected for two-stage combustion, NO_x levels are higher at lower values of excess air than for single-stage combustion. At the higher values of excess air, there is little difference between single- and two-stage operation. It is believed that this difference can be attributed to the configuration of the second air inlet flow path in the upper precombustor. Since air must now flow around more than half the liner to reach the second air inlet in this chamber, a significant conduction path for transferring heat – the water jacket – has been removed. Since not as much heat can be transferred out of the top zone, there is not as significant a reduction in temperature in this chamber as there could be if the liner was in contact with the water jacket throughout the entire circumference. As such, thermal NO_x is not as significantly reduced.

With this configuration, the multiple air inlets tend to increase combustor performance by redistributing the combustion air more uniformly throughout the precombustion chambers. This also tends to explain why at lower values of excess air, NO_x levels are higher for the two-stage mode than for the single-stage mode. Since at the lower excess air levels the two-stage approach provides a better distribution of the available oxygen, combustion improves over the single-stage approach. As more of the carbon in the ash burns out, the temperature in the combustion chamber increases; therefore, the formation of thermal NO_x increases.

A different CWS had been tested to evaluate its effect on system performance. The CWS used in the series of two-stage combustion tests was made from deep cleaned, micronized coal. Two different CWS's were used: UE3-116-MCW-F and UE3-204-MCW-F, which contained 1.35 and 1.32 percent ash in the base coal, respectively. In addition to this series of tests, one test was performed using high-ash coal. The CWS used in this test was designated UE3-205-MCW-F. The base coal in this CWS came from the same seam as the deep cleaned coal; however, it contained 6.32 percent ash. In addition to this, the coal was pulverized instead of being micronized. This gave the coal particle in the slurry a mean particle size diameter of 31.8 microns.

The reason for testing the system with such a different fuel had to do with the difference in the ash fusion temperature between the deep cleaned and high ash coals in the slurries. The deep cleaned coal used in the standard

Figure 2.8 NO_x Emissions vs Excess Air

CWS supplied by Energy International Inc., had an initial ash fusion temperature of 2150°F with a softening temperature of 2300°F. This tended to lead to slag formation on the silicon carbide parts of the IRIS combustor. The higher ash coal used in the UE3-205-MCW-F had higher ash fusion temperatures, with an initial fusion temperature of 2570°F and a softening temperature in excess of 2700°F.

For the test with the high-ash CWS, the combustor was operated at an input rate of 118,900 Btu/hr with 30-percent excess air and was tested in the two-stage mode of operation. The combustion efficiency for this test was found to be 97.4 percent based on analysis of ash collected by the bag filters. This test was encouraging in that slag did not appear to form on any of the precombustor surfaces. A problem with using this slurry was that ash particles tended to be separated out in the precombustor sections too well. This ash layer appeared to be free of carbon in that it was light brown in color. The main problem this ash layer posed was that if it continued to build up, it is expected that it would have altered the aerodynamics of the IRIS combustor in a negative way.

For the tests that were conducted this quarter, new partitions constructed of silicon carbide were tried. Upon initial startup, the silicon carbide rings cracked at various locations; however, since these partitions are supported from below, the cracks did not cause any structural problems. As the unit was operated with CWS, a layer of slag built up on the partitions. This layer of slag tended to hold the cracked silicon carbide partitions tightly together as if the plates were not broken at all. As with previous tests, the layer of slag formed on the silicon carbide partitions and was not present on the Hastalloy combustion chamber liners. For the considered test period, there was no indication that the layer of slag adversely affected the system performance.

During the report period, the slurry atomization process was accomplished by means of the supersonic CWS atomizer, which worked very well. Typical atomization air requirements ranged from 1.80 to 2.28 pounds of compressed air to 1 pound of CWS. The supersonic atomizer provided reasonable time for atomization, which allowed the startup procedure to be simplified.

The previous method of starting the IRIS combustor was to have oil fire axially downward from a modified oil burner nozzle and to inject CWS through the atomizer once the upper zone wall temperature had reached about 1800°F. Since the supersonic atomizer can atomize fuel oil fairly well, on startup, oil is injected in both the axial oil burner nozzle and in the supersonic atomizer. This preheats the upper chamber rapidly and allows CWS to be burned at full load without any supplemental fuel, in less than three minutes, as shown in Figure 2.9.

Figure 2.9 Startup Procedure

2.2. HEAT EXCHANGER LIFE-CYCLE TESTING AND OPTIMIZATION

The shell-and-tube heat exchanger's performance in the system was also studied during the report period. Two aspects of the heat exchanger performance were of particular interest: clean heat exchanger characteristics and the effect of fouling on the heat exchanger performance.

It was found that the performance data for the clean heat exchanger are higher than what the theory predicts for convective flow (as shown in Figure 2.10). This is due to the effect of thermal radiation from the particles to the heat exchanger walls.

Evaluating the heat exchanger fouling characteristics is important. In order to keep track of the rate of fouling, the heat exchanger was first thoroughly cleaned, then operated and monitored over an extended period of time. A total of 35 operating hours was accumulated for the data shown.

Heat exchanger fouling, in terms of a decrease in the overall heat transfer coefficient as a function of time, is shown in Figure 2.11. The gas side Reynolds numbers were $Re = 500$ through 580. Though 35 hours of operation is not enough time to make a definitive conclusion on fouling, the overall heat transfer coefficient does decrease with time. As more hours of operation are accumulated on the heat exchanger, the rate of fouling will be determined. These data will be used to determine the time interval required between cleanings. Also, methods for cleaning the heat exchanger (manual or automatic) are being studied.

2.3 BAGHOUSE LIFE-CYCLE TESTING AND OPTIMIZATION

The baghouse in the system worked without any deviation from normal operation. However, in order to optimize this subsystem and select an appropriate filter, an analysis of the particle size distribution of the fly ash collected in the baghouse was performed. The sample used for this analysis was obtained from a single-stage combustion test that has a combustion efficiency of 98.4 percent. A bar chart showing the particle size distribution is shown in Figure 2.12, and a logarithmic probability distribution is shown in Figure 2.13. In referring to Figure 2.13, it can be seen that the logarithmic distribution is linear, and that 50 percent of the distribution is below 11.2 microns. Knowing these data is a necessary prerequisite to select the filter with the required collection efficiency.

2.4. FABRICATION OF THE THIRD-GENERATION FURNACE

The life-cycle testing, optimization, and refining of the second-generation furnace were the major R&D activities during the report period. In parallel, work began on fabrication of the final laboratory prototype furnace, the third-

Figure 2.10 Heat Transfer in Shell-and-Tube Heat Exchanger

Time (Hours Since Heat Exchanger was Cleaned)

Figure 2.11 Effect of Fouling in the Heat Exchanger

Figure 2.12 Particle Size Distribution in the Fly Ash

Figure 2.13 Cumulative Particle Size Distribution in the Fly Ash

generation furnace. Under this work, fabrication of the various components that required machining has been completed. In addition to this, nonfabricated components have also been procured, including an air handling unit that will be modified to serve as the hot-water-to-warm-air heat exchange unit for transferring heat from the furnace loop to the residential environment.

3. SUMMARY STATUS ASSESSMENT AND FORECAST

During this report period, work continued on the life-cycle testing, optimization, and refining of the second-generation furnace assembly, which comprises all the major system components: the combustor, heat exchanger, and baghouse, as well as the auxiliary subsystems. The main emphasis of the combustor testing was to determine the optimum size and location of the air inlets in the primary combustion chambers to provide high combustion efficiencies with minimal agglomeration of unburned coal on the upper partition. Testing has revealed that using a single air inlet in the upper primary chamber situated about 70 degrees upstream from the typical agglomeration site produces a combustion efficiency of 99.0 percent while producing no agglomeration.

Testing this quarter also concentrated on evaluating the fouling effect on the heat exchanger performance. A steady decrease in time of the overall heat transfer coefficient in the heat exchanger has been observed. The effect of fouling on performance and required cleaning intervals is being evaluated.

In order to optimize the baghouse and select an appropriate filter, an analysis of the particle size distribution of the fly ash collected in the baghouse was performed. Fifty percent of the particles are smaller than 11.2 microns.

During the next quarter, life-cycle testing of the second-generation furnace will continue to identify areas needing further development. Also, fabrication of the third-generation furnace will be completed.

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