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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period February 1, 1989 – April 30, 1989

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

July 1989

Work Performed Under Contract DE-AC22-87PC79650

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

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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 concept development, including a novel state-of-the-art Inertial Reactor with Internal Separation (IRIS) combustor, enabled the first-phase program objectives to be met:

- 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 third quarter of Phase II.

During the report period, life-cycle testing, optimization, and refining of the second-generation furnace continued. At the same time, the third-generation furnace was fabricated and assembled, and life-cycle testing of the third-generation furnace began. 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 THIRD QUARTER OF PHASE II OF THE PROGRAM

2.1 LIFE-CYCLE TESTING AND OPTIMIZATION OF THE SECOND-GENERATION CWS WARM-AIR FURNACE

During this quarter, life-cycle testing continued on the second-generation Coal Water Slurry (CWS) Warm-Air Furnace (Figures 2.1 and 2.2). Specifically, the purpose of these tests was to determine how the combustion efficiency of the units changed as hours of operation accumulated.

For the testing conducted this quarter, the IRIS combustor was operated with air admitted only in the upper chamber. The upper chamber was further configured to have only one air inlet, located about 70 degrees counterclockwise (upstream) of the point where the atomizer CWS makes contact with the combustion chamber liner. In testing last quarter, this configuration produced high combustion efficiencies and minimized the agglomeration of coal particles on the upper partition.

During this quarter, the furnace operated for 54.5 hours and burned 691.1 pounds of CWS. If the total time that the unit operated in this configuration is considered, then the furnace has operated for about 90 hours and has burned 1,000 pounds of CWS.

During testing, the only maintenance that was performed on the system was to clean the bag filters twice to obtain ash samples for analysis. A plot showing how bag filter pressure drop changed as a function of time for 27.5 hours of operation is shown in Figure 2.3. For this particular test period, the combustor achieved a combustion efficiency of 99.6 percent, while the unit was operated with approximately 30 percent excess air. It should be noted that the unit was not operated continuously for 54.5 hours. Instead, testing occurred over many days, with the unit cycled on and off 14 and 5 times, respectively, for the 27.5- and 27-hour tests.

During testing this quarter, some ash was found to build up on the silicon carbide upper and lower partitions. The majority of the buildup was found on the lower partition, where it tended to reduce the size of the central opening. As has been found in previous tests, ash did not tend to build up on the combustion chamber walls which were constructed of Haynes alloy 188. Though ash buildup tended to alter the lower chamber geometry, it did not have an adverse effect on combustion efficiency. Test results yielded the highest combustion efficiencies to date. Fouling of the vertical shell-and-tube heat exchanger has continued to be monitored this quarter. To date, the heat exchanger has operated for 89.5 hours since its last cleaning. During the first 35 hours of operation, conducted in January 1989, a steady reduction in overall heat transfer coefficient seems to have occurred. This is shown in Figure 2.4.

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Figure 2.1 Photograph of Second-Generation Furnace

Figure 2.2 Schematic of Second-Generation Furnace Facility

Figure 2.3 Bag Filter Pressure Drop in the Second-Generation Furnace

Figure 2.4 Heat Exchanger Fouling Characteristics in the Second-Generation Furnace

where the overall heat transfer coefficient has decreased slightly with time for the period between 35 and 89.5 hours of operation. For the data presented in Figure 2.4, the gas-side Reynolds number varied from 500 to 580 while the water-side conditions remained constant.

Though a period of 89.5 hours of operation is insufficient to reach a definitive conclusion on heat exchanger fouling, it is not that unexpected that the rate of decrease in the overall heat transfer coefficient should level off. Upon examination of the heat exchanger, it was found that the ash layer that has built up on the heat transfer surfaces is very powder-like and not very sticky. As such, it comes off the heat exchanger tubes fairly easily. For this reason, it is assumed that eventually an equilibrium ash layer thickness will be achieved on the tubes.

As a layer of ash builds up on the heat exchanger tubes, the gas velocity will tend to increase since the flow area available to it has decreased. The high velocity in the tube would tend to erode the ash layer at a higher rate, and such an equilibrium should be reached between ash deposition and ash entrainment.

2.2 FABRICATION AND ASSEMBLY OF THE THIRD-GENERATION CWS WARM-AIR FURNACE

Work on this task has been completed during the report period (Figure 2.5). The design of the third-generation furnace (the final laboratory prototype furnace) was based on modifications made to the previous, second-generation model.

Both the third-generation furnace and the second-generation furnace employ the same major individual components and the same basic design principles, although the design arrangements for these furnaces are different. The design arrangement for the third-generation furnace is depicted in Figure 2.6. The furnace is 4.8 ft high and requires 13.5 ft² of floor space.

The third-generation furnace includes the following primary components and subsystems:

- The IRIS combustor with two partitions forming two combustion chambers
- Shell-and-tube heat exchanger
- Bag-type ash collection subsystem
- Primary ash collection box

Figure 2.5 Photograph of Third-Generation Furnace

1. Air Handling Unit
2. Baghouses
3. Primary Ash Collector
4. Combustor
5. Heat Exchanger

Figure 2.6 Third-Generation Furnace Arrangement

- Fuel delivery subsystem comprising the CWS storage tank with agitator and peristaltic pump
- Air-assist atomizer with air compressor
- Fuel ignition subsystem
- Air handling unit

The IRIS combustor remains the key system component. In the third-generation furnace, the upper and lower partitions of the IRIS combustor were configured with segmented silicon carbide pieces. The purpose of using segmented pieces was to keep radial temperature gradients from cracking the silicon carbide. The partitions are supported by a layer of insulation and by a support finger plate constructed of Haynes alloy 230. The alloy 230 finger plate is clamped between water-cooled flanges, and in this way it acts as a fin, to regulate its tip temperature. The liners for the upper and lower chambers were constructed of alloy 230, with only a single air inlet being used in the upper chamber. For the head liner, a piece of 1/8-inch-thick, segmented alloy 230 was used.

The IRIS combustor as well as the other components and subsystems have been described in more detail in the previous quarterly reports and in the final report DE-AC22-87PC79650-8 for the first phase of the program.

Although the basic design principles remain unchanged for the second- and third-generation furnaces as well as for the individual components and subsystems in these furnaces, some differences between the furnaces can be noticed. The most important differences are:

- The third-generation furnace (Figure 2.6) is designed as a stand-alone heating furnace. It incorporates the air handling unit (No. 1 on figure) and blower, pump, and control box as part of the furnace. In contrast, the second-generation furnace was designed more as an experimental unit for which modifications could easily be made. For example, the air handling unit, pump, and blower were not integrated into the unit.
- The second-generation furnace employs a single baghouse. In the third-generation furnace, a dual-baghouse design was chosen. In this design, the products of combustion can be alternated from one baghouse to the other. In this manner, the bag filters in one house can be cleaned while it is off-line. In the second-generation IRIS combustor, it was found that since the combustor pressure drop is so low, any attempt to clean the bag filters by air pulsing tended to blow coal particles back through the combustor and out the air inlet. Therefore, it is much easier to clean the bag filters when the baghouse is off-line.

2.3 LIFE-CYCLE TESTING AND OPTIMIZATION OF THE THIRD-GENERATION CWS WARM-AIR FURNACE

For the shakedown test, the standard micronized, deep cleaned, coal water slurry that has been burned for the past several months was used. The unit operated on average with 30-percent excess air, and ran at an input rate of 91,400 Btu/hr. In this particular test, a combustion efficiency of 98.4 percent was obtained, based on a chemical analysis of ash collected in the baghouse. As has been noted in previous tests, some ash started forming on the silicon carbide parts in the combustor; however, none was evident on the metallic alloy 230 liners.

After the shakedown test, life-cycle testing and optimization of the furnace started. Before this testing began, the combustor, heat exchanger, and baghouses were thoroughly cleaned. The reason for thoroughly cleaning the unit was to obtain baseline data on all the components, and then to monitor how their performance changes as a function of time.

For testing this quarter, the furnace operated for a total of 35 hours and burned 314.4 pounds of coal water slurry, with average tests lasting 6 hours. For the particular fuel used in this month's testing, this translated into an average input rate of 87,640 Btu/hr. For the 35-hour test period, analysis of ash collected in the baghouse indicated that the furnace operated with an average combustion efficiency of 98.9 percent.

Observations of the combustor have shown that ash tends to build up on the silicon carbide partitions, with the majority found on the upper partition. Buildup has also occurred on the lower partition. However, this buildup is softer than the ash that has been deposited on the upper partition. Though buildup is occurring on the partitions, up to this point changes in combustor performance have not been observed.

The combustor design refinement and optimization included the combustor head liner and start-up oil burner nozzle. In particular, new configurations of the combustion head liner have been tested.

Until now, the head liner had been constructed of a single piece of Haynes alloy 230 that was 0.125 in. thick. The liner was slotted to prevent distortion due to radial temperature gradients.

The metallic liners have worked well both in the second- and third-generation furnaces, but, since alloy 230 has a maximum continuous operating temperature of 2200°F, care must be taken to provide adequate cooling. Even with adequate cooling, scale has started to form at the center of the original head liner used for the majority of tests performed to date. To avoid further scaling problems, a head liner made of silicon carbide was constructed and

tested. The liner was made of 0.25-inch-thick nonimpregnated silicon carbide that had been cut into individual wedges. A layer of 1/2-inch ceramic fiber insulation was placed behind the silicon carbide wedges in order to limit the amount of heat transfer from the head. In testing conducted to date, the silicon carbide liner operated well, with no problems. The segmented design allows the individual pieces to expand uniformly under radial temperature gradients and has prevented tensile stresses which would crack the brittle silicon carbide.

Another modification made to the combustion chamber head included the start-up oil burner nozzle. In order to start the furnace, it is necessary to preheat the combustor by burning No. 2 home heating oil that is fired axially downward from the center of the combustor head for several minutes. As the oil is pumped through the atomizing nozzle, the oil cools the nozzle and prevents it from overheating. However, as combustion operation is switched over to CWS, the oil is shut off, and the nozzle quickly overheats and melts.

In the past, the oil nozzle assembly was removed and a sight port was installed to observe how well the combustor was operating. This approach is not possible outside of the laboratory, and, in order to achieve the level of operation that is required in a residential furnace, the oil burner assembly must remain in the unit. To accomplish this, a cooling coil was attached to the base of the nozzle, and a small amount of water was pumped through it as the furnace burned CWS. This prevented the nozzle from overheating. In order to keep the nozzle tip from being clogged by coal particles, a small bleed flow of compressed air is passed through the nozzle to keep the tip clean. The compressed air comes from the compressor that supplies compressed air to the supersonic CWS atomizer.

This approach has worked very well and has kept the oil burner nozzle functional for tests that have lasted for up to four hours while firing CWS. Though the nozzle cooling scheme protects the oil burner nozzle, a problem has been discovered with the high-voltage ignition electrodes. As the dual electrodes are left in the combustor, coal particles and ash tend to build up on the base. This causes the high-voltage spark to jump at the electrode base instead of at the tip. Spark plug and glow plug ignitors will be used to correct this condition.

Life-cycle testing is also very important for evaluating the heat exchanger performance. During this quarter, heat exchanger fouling has been carefully monitored. As an indication of fouling, the overall heat transfer coefficient, based on the tube inside area, is plotted as a function of time in Figure 2.7. As seen in Figure 2.7, there is a rapid decrease in the overall heat transfer coefficient; yet, as time increases the rate of decrease does not appear to be as great.

Another indication of heat exchanger fouling is the gas-side pressure drop. Heat exchanger pressure drop as a function of time is plotted in

Figure 2.7 Heat Exchanger Fouling (Third Generation)

Figure 2.8, where it can be seen that there is a steady increase in pressure drop with time. Though the heat exchanger pressure drop does increase with time, its magnitude is very small compared with the total system pressure drop. For example, the normal combustor operating pressure drop is 2 in. w.c. whereas the heat exchanger pressure drop is on the order of 0.1 in. w.c.

Currently, the third-generation furnace is manually controlled. By means of a single switch, the new control system can provide totally automated control of the furnace through startup and shutdown of the system. The controls for a furnace that burns CWS are quite different from its oil and gas counterparts. In addition to the fuel handling complexities, during a long burn the system pressure drop changes due to the bag house filter pressure drop increasing as fly ash is collected. To overcome this problem it was decided to use a closed-loop control system that adjusted the induced draft-blower speed to maintain a predetermined combustor pressure drop. All the components for the control system have been ordered, and assembly is set to begin next quarter.

2.4 MANUFACTURING PROTOTYPE DESIGN

The third-generation furnace is considered the final laboratory prototype and will be used as the basis for a manufacturing prototype. The preliminary drawings of the first manufacturing prototype supplied by our manufacturing partner, Yukon Energy Corporation, were reviewed, and appropriate changes were made. The revised drawings (Figure 2.9) have been sent back to Yukon Energy for their comments. The manufacturing prototype employs a gas-to-air heat exchanger and an air-cooled IRIS combustor. The manufacturing and operating cost evaluation for this design is scheduled for completion in September 1989.

Figure 2.8 Heat Exchanger Fouling (Third Generation)

Figure 2.9 CWS Warm-Air Furnace

3. SUMMARY, STATUS ASSESSMENT, AND FORECAST

During the report period, work continued on the life-cycle testing, optimization, and refining of the second-generation furnace assembly, which comprises all the major furnace components: the combustor, heat exchanger, and baghouse, as well as the auxiliary subsystems. The furnace has operated for about 90 hours, and has burned 1,000 pounds of CWS. During testing, the only maintenance that was performed on the system was to clean the bag filters to obtain ash samples for analysis.

Concurrent with testing the second-generation furnace, fabrication and assembly of the third-generation furnace was completed, and a life-cycle testing and optimization process for this furnace has started. In contrast to the second-generation furnace, which was designed more as an experimental unit, the third-generation furnace is a stand-alone heating unit incorporating the standard air handling system, blower, pump, and control box as part of the furnace. During the report period, the third-generation furnace operated for a total of 35 hours, and burned more than 300 pounds of CWS, with average tests lasting 6 hours.

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

At this stage, some preliminary general forecasts concerning the current, second phase of the program can be formulated. The development of an economically viable CWS-fired residential warm-air space-heating system is proceeding successfully, and the second-phase program objectives definitely will be met. Indeed, life-cycle testing demonstrated that the system has stable operation with dual-fuel capability, combustion efficiency exceeds 99 percent, steady-state efficiency exceeds 80 percent, response time is less than 5 minutes to full load, and turn-down ratio is 4:1.

Based on the analysis of the life-cycle test data, the follow-on activities representing the next step to the furnace commercialization can be recommended:

- Alternative material selection, specifically for refractory-lined partitions and metal/refractory-lined walls in the IRIS combustor
- Alternative partition cooling arrangement
- Control system optimization
- Fabrication and testing of the Tecogen/Yukon direct gas-to-circulation air unit with the air-cooled IRIS combustor

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