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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period February 1, 1988 - April 30, 1988

By

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

June 1988

Work Performed Under Contract No. DE-AC22-87PC79650

Tecogen Inc.

**A Subsidiary of Thermo Electron Corporation
Waltham, Massachusetts**

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1. INTRODUCTION

The objective of the Coal/Water Slurry (CWS) Fired Warm-Air Heating System program is the development of a reliable, efficient, compact and safe CWS-burning residential furnace. This report summarizes results of the fifth quarter of the first phase of the program effort carried out by Tecogen Inc.

During the first phase of the program, Tecogen is developing several key components of the furnace. These components may be grouped into three general areas:

- Components directly related to combustion processes (i.e., combustion chamber, burner, and atomizer)
- A heat exchanger that transfers sensible heat from the flue gases to a circulating water loop
- A gas cleanup system

Figure 1.1 is a schematic diagram that shows these components in relation to an entire heating system that starts with fuel delivery and storage and ends with ash disposal. This work encompasses the section enclosed by the dashed line.

The goal of this program is to develop a furnace that meets the following design criteria:

• Fuel	CWS as primary fuel and No. 2 heating oil as secondary fuel
• Thermal Input	100,000 Btu/hour
• Ignition	Automatic
• Safety	Comparable to oil-fired residential heating systems
• Steady-State Efficiency	Greater than 80 percent
• Combustion Efficiency	Greater than 99 percent
• Daily Maintenance	None
• Scheduled Maintenance	Less than twice a year
• Size Constraints	Height less than 6 feet
Floorspace less than 15 square feet
• Response Time	Less than 5 minutes to full load
• Service Life	Greater than 20 years

Figure 1.1 Tecogen Inc. CWS-Fired Heating System

During the fifth quarter, work continued on Task 1.70, Testing and Development of Initial Prototype Components. It was found from this testing that the entire furnace system, including the combustor, peristaltic pump, Y-jet atomizer, and heat exchanger, performed reliably. In particular, the combustor, which is best denoted as an Inertial Reactor with Internal Separation (IRIS) because it uses centrifugal forces to detain particles, achieved a carbon conversion efficiency of over 97 percent.

Work also continued on fabrication and assembly of a second-generation, Proof-of-Concept system. This new unit incorporates a water-cooled combustor in place of the previous air-cooled unit. This will enable operation with less excess air and higher flame temperatures. Also, a heat exchanger with larger gas passages (tube diameter) to reduce the effects of fouling was built.

During the next quarter, characterization and development of this new system will take place.

2. WORK PERFORMED DURING THE FIFTH QUARTER

During this quarter, work was continued on Task 1.70, Testing and Development of Initial Prototype Components. Throughout this period, performance testing of the entire furnace system continued, using the Y-jet atomizer. Also, fabrication of the new, second-generation furnace system continued. The second-generation combustor was designed to be modular in construction and allowed for the easy installation of alternative, high-temperature, combustion chamber liners.

2.1 TEST RESULTS

Testing this quarter continued with the original stainless-steel prototype combustor using CWS as the fuel.

2.1.1 CWS Fuel Properties

The particular CWS used in this testing was supplied by Energy International, Inc. This slurry was 64.84 percent by weight coal, had a specific gravity of 1.175, and exhibited a shear thickening behavior with a power law index of 1.79. The deep-cleaned coal used in the slurry had the following properties:

- Heating Value 15,056 Btu/lbm (dry)
- Weight Percent Ash 1.35% (0.897 lbm/MMBtu)
- Weight Percent Sulfur 0.58% (0.385 lbm/MMBtu)

In addition to these the coal ash had the following properties:

- Ash Fusion Reducing
- Temperatures Initial - 2120°F
 Softening - 2300°F
 Fluid - 2410°F

2.1.2 Summary of Test Results

Testing continued on the prototype furnace system shown schematically in Figure 2.1. A photograph of the laboratory facility is shown in Figure 2.2. In summarizing the testing that has been performed, the prototype system has operated at firing rates from 86,700 to 102,400 Btu/hr, with typical test durations of two to four hours. Tests are run for this period of time to ensure that a sufficient amount of ash is collected to allow for chemical analysis.

Figure 2.1 Schematic of Laboratory Facility

Figure 2.2 Laboratory Facility

2.1.2.1 Combustor Performance

Chemical analysis of the collected ash by a commercial testing laboratory was used to determine the combustor's carbon conversion efficiency. As illustrated in Figure 2.1, ash samples can be collected in two separate locations. The first location is the combustor ash collection box, which is directly below the IRIS combustor, and remains hot throughout a given test. Any combustible matter present in the ash collected here can still burn. Due to this fact, analysis of ash collected at this location typically has a carbon conversion efficiency on the order of 99.9 percent.

The second location where ash is collected is in the ash collection system directly below the heat exchanger. Since any combustible matter contained in the ash that passes through the heat exchanger is quickly extinguished by the cold walls, ash collected downstream of the heat exchanger provides a lower bound indication of how well the combustor is performing. The actual carbon conversion efficiency of the combustor is the mass weighted average of the carbon conversion efficiencies of the ash collected in the hot combustor ash collection box and the cold ash collection system directly below the heat exchanger. Since the carbon conversion efficiency obtained from analysis of ash collected in the cold ash collection system is the lower of the two efficiencies, this value is used as a conservative indication of the performance of the combustor.

Results of combustor testing in terms of carbon conversion efficiency are shown in Table 2.1. In addition to the carbon conversion efficiency, precombustor wall temperature, excess air, and inlet air temperature are also tabulated. Table 2.1 shows that carbon conversion efficiencies ranging from 96.2 to 97.1 percent have been obtained. An important finding in these tests was that, in order to obtain stable combustion with high carbon conversion, precombustor wall temperatures in excess of 1800°F were necessary.

The original IRIS combustor was constructed of stainless steel, to enable modifications to be readily made. The combustor walls were cooled by the combustion air, although finned air passages were employed around the chamber. Therefore, heat transferred from the lower main combustion chamber is used to preheat the inlet air, which aids in drying the atomized slurry, and thus the heat is not removed from the system.

We recognized that this approach of air preheating combined with a stainless-steel combustor would limit the allowable operating temperature; however, we chose to operate the prototype with elevated temperatures in order to achieve good combustion. Even at the elevated temperatures, a considerable amount of excess air ranging from 55

TABLE 2.1
COMBUSTOR PERFORMANCE

Case	Reference Data File Number	CO ₂ (Excess Air) (%)	Precombustor Wall Temp. (°F)	Inlet Air Temp. (°F)	Minimum Carbon Conversion Efficiency (Heat Exchanger Ash) (%)
1	32 - 35	8.5 (110)	1850	--	96.6
2	38 - 39	8.8 (103)	1800	1110	96.7
3	40 - 41	11.2 (60.4)	1840	1300	96.2
4	43 - 44	11.6 (55.0)	1850	1500	96.8
5	47	~9 (~99)	1800	1000	97.1

to 110 percent, as shown in Table 2.1, was required to limit the flame temperature, to prevent melting the combustor.

To illustrate how the combustor temperature varies with position, Figure 2.3 shows the axial temperature distribution as a function of time from the initial cold startup on No. 2 heating oil to burning CWS. The data used in this plot were obtained from Case 4 (Table 2.1). Referring to Figure 2.3, temperature measurements were taken ranging from the precombustor, 3 inches down from the top of the IRIS combustor, to 29 inches down from the top, which is the bottom of the unit. For this particular test, the IRIS combustor was heated with No. 2 heating oil for about 30 minutes. At that time, the Y-jet atomizer was inserted tangentially into the precombustor. The atomized CWS started to burn, and the oil was shut off.

2.1.2.2 Furnace System Performance

The best indication of how well the entire furnace system is performing is by the overall thermal efficiency; i.e., the amount of heat recovered in the water flowing through the heat exchanger divided by the thermal input of the furnace, based on the CWS higher heating value. In testing to date, thermal efficiencies approaching 70 percent have been obtained. However, because a large amount of excess air is needed (up to 110 percent) to limit the flame temperature in this particular combustor, significantly better performance is expected in future designs operating with 25 percent excess air.

The excess air is detrimental to the system's performance for two reasons. First, the gases in the heat exchanger flow under laminar conditions and, thus, the additional gas velocity has only a small positive influence on the gas side overall heat transfer coefficient. Second, the additional mass flow rate contributes significantly to the sensible heat lost up the stack.

To illustrate how the shell-and-tube heat exchanger performed during the furnace testing, Figure 2.4 is a plot of the gas inlet and outlet temperatures, measured with aspirating thermocouples, for the duration of test Case 4 (Table 2.1). Based on the gas and water inlet and outlet temperatures, along with the total amount of heat transferred, the heat exchanger effectiveness and overall heat transfer coefficient were determined, as shown in Figures 2.5 and 2.6. Figure 2.5 shows that the shell-and-tube heat exchanger operated with an effectiveness of about 87 percent while burning CWS. This corresponds to an overall heat transfer coefficient of $3.55 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$, as shown in Figure 2.6. Under these conditions, theory predicts that the overall heat transfer coefficient should be $2.47 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. This considerable improvement of 44 percent can be explained; it is due to the strong vortex established in the combustor, and the considerable amount of prerotation of the gases entering the heat exchanger. This high degree of prerotation is very analogous to having twisted tape inserts in the tubes.

Figure 2.3 Combustor Temperature Profile versus Time - Case 4

Figure 2.4 Heat Exchanger Gas Temperature versus Time - Case 4

Figure 2.5 Heat Exchanger Effectiveness versus Time - Case 4

Figure 2.6 Overall Heat Transfer Coefficient versus Time - Case 4

Work with twisted tape inserts under laminar flow conditions* has shown that a significant increase in heat transfer can be achieved under these conditions with a much lower effect on pressure drop than is usual in the turbulent flow regime.

Currently, only carbon dioxide and carbon monoxide emission levels from the system have been measured. Carbon monoxide levels are typically between 100 and 250 ppm at carbon dioxide levels of 6.5 to 11.0 percent. Recently, a pulse fluorescent sulfur dioxide analyzer has been obtained and will be used in future testing to determine SO_2 levels. In addition to this, NO_x will also be measured using a chemiluminescent analyzer that is available.

2.2 NEW COMBUSTOR

The present, stainless-steel prototype combustor demonstrated that the IRIS concept can burn coarsely atomized CWS with fairly high combustion efficiencies. However, it had to be operated at lower wall temperatures than desired which placed a limit on attempts to improve combustion efficiency any further. Also, the large amount of excess air needed to limit the flame, and therefore the wall temperature, has an adverse effect on the heat exchanger and associated furnace system performance. To demonstrate the performance at higher temperatures, a new IRIS combustor was designed. The new combustor is modular in design, which allows the volume to be varied and also allows multiple partitions in the precombustor section, if desired. Also, provisions have been made to facilitate the changing of combustion chamber liners to test different high-temperature materials.

During this quarter, construction of all the major components of the combustor was completed, and assembly of the new system began. A schematic diagram of the new laboratory furnace facility is shown in Figure 2.7. In addition to the new combustor, a new primary ash collection box has been designed that uses a secondary cyclone to trap more ash in the hot section of the furnace, where any combustible matter can still burn off. Also, a new heat exchanger has been designed and fabricated. The new heat exchanger uses 3/4-inch tubes instead of the 5/8-inch tubes used in the old design. The size of the tubes was changed to reduce the effects of fouling by the fly ash on the heat transfer surfaces.

Figure 2.7 illustrates that the new combustor employs water cooling at various key locations to limit the outer skin temperature and reduce the need for an excessive amount of insulation. Also, water-cooled walls tend to minimize thermal distortion.

*Hong, S.W. and Bergles, A.E., "Augmentation of Laminar Flow Heat Transfer in Tubes by Means of Twisted-Tape Inserts," Trans. ASME, J. Heat Transfer, 98, pp. 251-256 (1976).

Figure 2.7 Schematic of Second Generation Furnace Facility

The cooling water used to cool the combustor then enters the heat exchanger. The combustor thereby provides additional heat transfer surface for the furnace system.

Details of the combustor's construction, Figure 2.8, show the main combustion chamber of the IRIS. In referring to the figure, the combustor is lined with a high-temperature liner, in this case Hastalloy alloy 188, which can operate continuously in an oxidizing environment at temperatures up to 2200°F. Behind the liner is a layer of high-temperature ceramic fiber insulation. Behind the insulation is the water-cooled outer combustor shell.

Proper operation of the IRIS combustor depends on selectively detaining larger coal particles in the hot, precombustor zone. It is the job of the partition to do this effectively. Figure 2.9 shows the IRIS precombustion chamber with the tangential air inlet and the partition. The particular partition shown is constructed of high-temperature, insulating board. This was used because it can be easily cut and is inexpensive. By using this board for the partition, it is possible to very easily try different diameter openings to determine the effect of hole diameter on combustor performance. To enable the insulating board to survive in the abrasive environment of the precombustor, it is treated with a ceramic rigidizer that allows it to last for several hours of testing.

In order to burn CWS with the Y-jet atomizer, the precombustor must be preheated. To do this, the new combustor employs a modified oil burner nozzle assembly and electrodes. No. 2 heating oil fires downward through the nozzle assembly, as shown in Figure 2.10. Once the combustor is sufficiently preheated (about 3 minutes), CWS combustion occurs. The preheater assembly can be removed and replaced with a sight port to allow visual observation of the CWS flame.

As stated previously, all the major components for the new furnace system have been fabricated. Assembly of the various components into the new furnace has started and is almost complete. Figure 2.11 shows the assembly of the IRIS combustor in progress.

1268-N

Figure 2.8 IRIS Combustor, Main Combustion Chamber.

1269-N

Figure 2.9 IRIS Combustor, Precombustion Chamber and Partition.

1270-N

Figure 2.10 Oil Preheater Assembly

Figure 2.11 IRIS Combustor during Assembly

3. SUMMARY STATUS ASSESSMENT AND FORECAST

Figure 3.1 illustrates the progress to date – the program is on schedule. Work is proceeding on the only remaining major task, Task 1.70, Testing and Development of Initial Prototype Components, and will continue until the end of this phase of the program.

The results of this quarter's testing have shown that the current stainless-steel IRIS combustor is capable of operating with combustion efficiencies ranging from 96.2 to 97.1 percent when operating with a CWS input rate of 86,700 to 102,400 Btu/hr. However, since the original prototype combustor was designed for ease of modification instead of high temperature, a larger amount of excess air ranging from 55 to 110 percent was required to reduce the flame temperature.

Work this quarter also continued on constructing a new furnace system with a combustor that is capable of higher operating temperatures, along with an improved ash collection system and heat exchanger. Construction of the components for the new furnace has been completed, and assembly of the new furnace system is almost complete.

During the next quarter, testing of the new furnace system will begin. Different combustion chamber liners will be tested along with different partition opening diameters. This will be done in an effort to maximize combustion efficiency. Also, testing will be conducted on different startup scenarios in an effort to minimize the amount of time the system needs to operate with No. 2 heating oil before it can burn slurry. Testing during the next quarter will also include the measurement of SO_2 and NO_x levels.

Legend: Scheduled
Actual

Figure 3.1 Status Chart

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