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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period May 1, 1987 - July 31, 1987

By
F.E. Becker and L.A. Smolensky

September 1987

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 CWS-Fired Warm-Air Heating System program remains unchanged: the development of a reliable, efficient, compact and safe coal-water-slurry (CWS) burning residential furnace. This report summarizes results of the second quarter of the first phase of the program effort carried out by Tecogen, Inc.

During the first phase of the program, Tecogen, Inc., 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 flue gases to a circulating water loop.
- A gas-cleanup system.

During the second quarter of effort, Tecogen, Inc., scheduled the completion of Task 1.30 (System Analysis) initiated in the first quarter, 1987, and Task 1.40 (Component Analysis and Design). Tasks 1.50 (Fabrication and Assembly of Initial Prototype Components) and 1.60 (Laboratory Facility Modification) had been programmed for initiation with, respectively, about 25 percent and 50 percent of completion at the end of the second quarter.

The program is ahead of schedule: Tasks 1.30, 1.40 and 1.60 are complete; Task 1.50 is 75 percent complete; Task 1.70, Testing and Development of Initial Prototype Components, was planned to take place in the fourth, and subsequent, quarters; however, preliminary testing of some prototypical components is carried out.

2. WORK PERFORMED DURING THE SECOND QUARTER

2.1 TASK 1.30 - SYSTEM ANALYSIS

Figure 2.1 depicts the relationship among the furnace components as currently envisioned. The basic furnace components, which will be developed during the first phase of the program, are indicated within the dotted area on the figure.

The intended design will be of modular fashion for use not only with forced-air heating systems, but will also be applicable for use with hydronic (hot water) systems. In addition, the boiler will be capable of being used for making domestic hot water in a separate storage tank. In Figure 2.1, circulating hot water is split and directed to the hot water tank and to the air coil. It is not reasonable to assume that a homeowner would use a coal-based fuel for space heating and still have a separate gas- or oil-fueled hot water heater. As such, the investment and incentive in going to a coal-combustion-based heating system should be coupled to as many other uses as are practicable.

Three conceptual design layouts (Figures 2.2, 2.3 and 2.4) developed during the first quarter, 1987, illustrate feasible approaches to integrate the basic components - combustor, heat exchanger and gas-cleanup system. As can be seen, Figures 2.2 through 2.4 incorporate three different types of combustors, two types of heat exchangers and two types of gas-cleanup systems. These components are analyzed in the next section, and the most effective of them are selected for further development.

2.2 TASK 1.40 - COMPONENT ANALYSIS AND DESIGN

The three furnace component groups will now be discussed, and specific performance requirements will be generated for each one within the context of the overall criteria adopted in Task 1.10.

Figure 2.1 CWS-Fired Heating System Flow Diagram

Figure 2.2 Coal-Water-Fired Furnace - First Concept

Figure 2.3 Coal-Water-Fired Furnace - Second Concept

Figure 2.4 Coal-Water-Fired Furnace - Third Concept

System interdependencies will be elaborated upon in the presentation of the conceptual designs described below.

2.2.1 Component Description

a. Components Directly Related To Combustion Process

The fundamental goal of this group of components is the combustion of 100,000 Btu/hour of CWS with a carbon burnout exceeding 99 percent.

Studies of CWS combustion, cited in the literature survey reported in Task 1.20 Topical Report (report number TE4415-54-87), have shown that long residence times are important for good carbon burnout. However, such factors as high atomization (small droplets), air/slurry premixing, and preheating of combustion air all help to promote combustion intensity, reduce the time required for a given carbon burnout, and minimize combustor size.

Thus, in order to achieve a combustion efficiency exceeding 99 percent in a compact furnace, very high heat-release rates are required. A rate of 200,000 Btu/hr-ft³ (implying a 0.5 ft³ combustion volume) was chosen in Task 1.10. This is the most challenging technical problem to be addressed in the design of the combustion-related components, because the attainment of such high combustion intensities is unusual even in larger combustors, where sophisticated techniques are employed. On the residential scale such advances might not be confidently employed.

At least three approaches can be taken to promote high combustion efficiencies in the small volume available in a residential furnace: fine atomization, separation and retention of large particles, and recirculation of heat, hot gases, and unburned particles and droplets. Each of these approaches will be discussed.

Burnout time for given thermal conditions depends very strongly on droplet size. For example, burnout time for a 10-micron CWS droplet has been reported to be about 8 milliseconds, while for a 40-micron droplet, burnout time was closer to 150 milliseconds and for a 100-micron droplet up to 2.5 seconds, with carbon burnouts around 90 percent. Heat-release rates of $200,000 \text{ Btu/hr-ft}^3$ correspond to 300 to 400 millisecond residence times and thus droplets bigger than 50 to 60 microns will not have sufficient residence time for complete combustion.

Currently, average CWS droplet diameters produced in large boilers by twin-fluid atomizers are typically about 80 microns in diameter. In such boilers there is generally sufficient residence time to achieve complete carbon burnout. However, for a residential burner, this will result in an excessive appliance size, having a combustor length equivalent to that of the large boiler with a very small flow area or, alternatively, acceptable combustor length with large flow area and maldistribution of gases and especially solids over the combustor volume.

One method of ensuring high carbon burnout within the restricted combustion volume available is to require a very fine atomization of the CWS flow. While atomization of slurries is possible and has been studied in detail, practical application of pressure or twin-fluid atomizers (the most common techniques employed) to the residential scale has not been sufficiently studied. Pressure atomizers of the type used for paint spraying might be feasible.

Another atomization method - using ultrasonic energy - might be workable. Ultrasonic atomizers produce quite small droplets with minimal pressure requirements and low power consumption. Also, easy scaledown to the $100,000 \text{ Btu/hr}$ size is envisioned.

Each of these atomizers, when used without any method of selecting small or detaining large particles, must produce a flow of about 1 gal/hr of CWS droplets smaller than 50 to 60 microns in diameter. Developmental testing will be required to validate this approach.

A conceptually different approach also exists. If particles larger than the specified size can be detained in a combustion chamber until the required carbon burnout is achieved, then the stringent atomization specifications described above might be relaxed. The IRIS combustor shown in Figure 2.3 achieves this effect through the utilization of centrifugal forces to retain larger, more massive droplets or particles within a precombustion chamber, thus increasing residence time within a minimal volume.

It can be easily shown that the total pressure on the walls of a cyclone-type reactor is greater than the total pressure at the center of the vortex. This pressure difference may be employed to motivate axial recirculation of hot gases, particles, and droplets; such a concept is discussed further below. The return of enthalpy as well as dry and fine unburned coal particles from the hot combustion zone to the water-evaporation zone in this fashion contributes strongly to flame stability, turndown, and carbon burnout.

The three methods of combustion described above - fine atomization, selective retention, and axial recirculation - may be used in conjunction or separately to improve combustion quality.

b. The Heat Exchanger/Boiler

The heat exchanger/boiler provides a mechanism for the transfer of heat from hot gases produced in the CWS burner to a water loop. This circulating loop, in turn, heats air which warms the residence.

By specifying the rate of heat transfer from the combustion gases to the hydronic loop (based on a 100,000-Btu/hr thermal input), and the efficiency required of the furnace (taken as 80 percent), the fundamental heat-exchanger/boiler design criterion is defined.

However, the desire for a low-maintenance furnace might strongly affect boiler design. Specifically, plugging of heat transfer surfaces must be prevented and any erosion of tube fins, or plates must be minimal.

Here a tradeoff between small size (which implies compact, extended, and complicated surfaces) and resistance to plugging (which requires simple shapes and wide channels) must be made. Again component testing and economic analysis will define an optimum configuration.

c. Gas Scrubber

The primary purpose of the gas scrubber is to clean the flue gases before their introduction into the environment.

The flue gas needs to be scrubbed of particulates to be environmentally acceptable. After passing through the heat exchanger/boiler, giving up heat to the circulating-water loop, the combustion gases will be relatively cool. These gases will contain both fly ash and some unburned carbon. However, the amount of fly ash carried will depend upon the CWS specification, while unburned carbon will be a direct consequence of the degree of carbon conversion achieved.

Both wet- and dry-type gas-cleanup techniques have been examined. Both have advantages and disadvantages. Dry, bag-type filters are quite simple and reliable, but are not able to clean gases as thoroughly as wet-type scrubbers, and might have a higher pressure drop. Their simplicity, however, is quite attractive in the

residential setting. Specification of a proper filter material and subsequent testing will illuminate the consideration of bag filters.

A wet-type scrubber offers the advantage of quite good gas cleaning, but is clearly more complicated than a dry system. The Tecogen emphasis on manufacturability and viability in the residential marketplace has resulted in the favoring of the dry system, at least for preliminary prototype testing.

2.2.2 Discussion of Concepts

Let us analyze advantages and disadvantages for the individual components of the modular design concepts depicted in Figures 2.2 through 2.4. This analysis will allow us to arrange the best furnace design for further development, fabrication, and preliminary testing.

The most critical component in Concept 1 in Figure 2.2 is the combustor. The combustor, which defines the combustion volume, is used to facilitate the transfer of heat from the combustion gases to the primary circulating-water loop. Very fine atomization is clearly required here, for if CWS droplets are not small enough, coal particles will reach cold surfaces before they are burned, and combustion efficiency might be lower than expected.

Because of this need for fine atomization, ultrasonic atomization is considered to be a fundamental feature of Concept 1.

The second design concept, shown in Figure 2.3, is less dependent upon fine atomization for efficient combustion. A cyclone-type reactor, known as an IRIS, acting in this particular case as a pre-combustor detains relatively large coal particles and CWS droplets by restricting them from entering the combustion chamber. Because these larger particles are retained in the precombustor, residence times are larger and carbon burnout is rather high without requiring fine atomization.

Figure 2.5 depicts the operation of the IRIS precombustion chamber and the combustor. CWS droplets are introduced axially through the reactor center or with the primary air which enters the precombustor tangentially. A partition with a relatively small centrally located axial opening divides the precombustor from the combustor, and is the key to system operation: strong tangential flow will force larger particles and CWS droplets away from the central opening and toward the walls. These particles will not be allowed to leave the precombustor until they are at least partially burned, at which point aerodynamic drag will overcome centrifugal forces and particles will leave the reactor.

The temperature within the precombustor will be low enough to inhibit slag formation and prevent particles sticking to the reactor walls, yet sufficiently high for intensive water evaporation and coal combustion. This temperature will be verified experimentally. Combustion-air preheating and flue-gas recirculation, as well as heat-loss control, can be used to set the reactor temperature.

One variation of this combustor might include axial recirculation of hot gases and particles. The heat required to vaporize the water in a CWS burner is only about 3 to 4 percent of the heat of combustion and as such should have no substantial impact on the overall combustion process. However, this water is evaporated at the onset of the process, and will therefore significantly effect ignition, flame stability, and turndown ratio.

Recirculation of hot gases and particles might be accomplished within the combustor described above by utilizing the pressure differences which occur naturally in vortical flows (see Figure 2.6). In this case, due to centrifugal forces, the pressure near the combustor walls may be much higher than that in the zones along the combustor axis. This pressure difference is sufficient to motivate

1. Atomizer

2. Precombustor (Insulation Is Not Shown)

3. Combustor (Insulation Is Not Shown)

4. Refractory

Figure 2.5 IRIS Precombustion and Combustion Chambers
(Second Concept)

Figure 2.6 IRIS with Axial Recirculation

intensive recirculation. (For methods of calculation of this pressure distribution, see Smolensky, L.A., "Convective Electrothermal Furnaces," Moscow, 1972.)

Concept 2 employs a flue-gas/water heat exchanger, similar to that of Concept 1 to absorb flue-gas heat and transfer heat to a circulating-water loop. However, in Concept 2 a simple bag filter is employed to clean the flue gases: since no water spray is used, standard filtration materials are appropriate. Additional heat may be captured from the flue gases - after they are cleaned - perhaps using extended heat-transfer surfaces.

The bag filter forms a bucket in which ash is collected. This bucket may be disposable or reusable: bag cleaning might be accomplished by the homeowner or by utilizing compressed air from a compressor installed on the special truck which both delivers CWS to the household and removes fly ash.

The third concept (Figure 2.4) uses the same types of gas-clean-up and combustion systems as Concept 2, but employs a shell-and-tube heat exchanger with vertical bare tubes instead of the extended surfaces shown in Figures 2.1 and 2.2; thus, fouling and plugging of the heat-exchange surfaces are less likely.

Also, Concept 3 has a different precombustion system, using a cold-flow, cyclone-type separator instead of the precombustor of Concept 2, large CWS droplets are prevented from entering the combustor. Atomized CWS is introduced tangentially into the cyclone-type separator, and larger and smaller droplets are separated. Then, the fraction of larger droplets is returned to the atomizer, by way of the interim CWS tank, to be atomized again. Smaller droplets will proceed directly to the combustion chamber, where sufficient volume is provided to ensure complete burnout.

The precombustion/combustion system in Concept 3 is more complex than the IRIS combustor. The disadvantages of this system are related to the potential problems of CWS stratification and plugging cold-flow, cyclone-type separator.

2.2.3 Basic Design Choice

Based upon both analysis and experimentation, the various components described above have been synthesized into one basic concept which has been chosen as the primary focus of further development. Table 1 summarizes the choices which have been made, indicating both the primary and alternative concepts chosen.

The IRIS system was adopted over the other concepts presented above for several reasons. In particular, IRIS:

1. Provides higher carbon burnout.
Separation of relatively coarse and fine droplets and selective retention of larger coal particles result in longer solids residence time.
2. Improves combustion due to intensive turbulent mixing of solids and combustion air.
3. Lowers droplet agglomeration just after atomization.
Centrifugal forces promote spreading out of the cloud of atomized droplets leaving the atomizer, and thus the distances between individual droplets inside this cloud are increased.
4. Simplifies startup and reduces the time required for system preheating.
An oil-firing jet can be introduced through the primary-air inlet to preheat the precombustor. The relatively small volume of this chamber requires less time to reach slurry-ignition temperature.

TABLE 1
COMPONENTS SELECTED FOR FUTURE DEVELOPMENT

	COMPONENT	BASIC CONCEPT	ALTERNATIVE CONCEPT
1	Combustion System	IRIS	IRIS with Axial Recirculation
2	Gas/Water Heat Exchanger	Shell and Tube	Finned Tube
3	Flue-Gas Cleanup System	Bag Filter	Wet Scrubber

5. Increases turndown ratio.

Due to the higher concentration of solids circulating within the precombustor, higher temperature-stability and, therefore, lower load can be maintained.

6. Lowers NO_x emissions due to increased swirl and staged combustion.

The heat-exchange method chosen for the first system is of a shell-and-tube design. Hot combustion gases enter the tubes and are cooled by water which is circulated outside the tubes, in the shell.

A simple bag filter is employed to clean the flue gases; since no water spray is used, standard filtration materials are appropriate. The bag filter forms a disposable or reusable bucket in which ash is collected.

2.2.4 Design Specifications for the Selected Concepts

In this section, an examination of some issues relating to the design and the following fabrication of preliminary prototypical components, based upon the discussion of Section 2.1 will be made. Each component group will be discussed. The preliminary components thus fabricated will be used to verify the design concepts described above through testing, and will be used to design second-generation prototypes.

In any preliminary design, the number of variables is very large compared to the number of constraints, and so the designer must make many design choices based upon "intuition" or "reasonableness." The design of the CWS furnace is a particularly good example of this phenomenon. Since the science of CWS combustion is not sufficiently advanced, especially at the residential scale, to permit the objective determination of many design variables, such variables are just chosen, and the design iteration described in the technical proposal - design, fabricate, test, redesign, etc. - is begun. Here, we describe the beginning of the first step of this process.

So, for each component, those constraints which do exist will be described and then the design choices which have been made will be presented.

a. Combustion-Related Components

● Design Constraints

The CWS combustor is designed to burn roughly 100,000 Btu/hr of CWS (about 1 gal/hr) with a combustion efficiency of greater than 99 percent. Based upon the IRIS concept described above, it has an internal volume of about 0.5 ft^3 in order to meet the combustion-intensity goal of 200,000 Btu/hr-ft³.

● Design Choices

Many choices must be made in the design of the initial prototype combustor. First, the combustor material must be specified; although ceramic materials are attractive and will probably be employed in the final design (and indeed in subsequent prototypes), for the initial prototype stainless steel is chosen. Steel is favored primarily because it is simpler, quicker, and less expensive to fabricate than SiC. Also, since a great deal of useful learning will take place during the testing of this initial prototype combustor, it makes sense to make adjustments on a flexible, cheap, and easily repairable prototype.

Given an internal volume of 0.5 ft^3 , the diameter and length of the burner must be chosen, and the location of the partition dividing the combustor from the precombustor must be defined. A combustor diameter of 8 inches, length of 17 inches, and precombustor length of 6 inches are chosen.

Next, the vortex velocity in the precombustor will be taken as 15 ft/sec (cold). This implies, with an inlet airflow of about 20 to 40 scfm an inlet area (in the precombustor) of around 3.2 square inches.

A 0.25-inch wall thickness for the combustor is chosen.

Now, in order to recirculate enthalpy from the combustion zone to the evaporation zone, it is decided to pass the incoming combustion air along the walls outside of the combustor, thus preheating this combustion air; a finned outer surface will encourage heat transfer from the combustor to the incoming air.

Preheating of the combustor will be accomplished by firing fuel oil in the precombustion zone. Then CWS will be introduced into the hot precombustor in several fashions to test different atomization methods; the combustor will be fabricated to facilitate such experimentation.

The combustor will be built without an axial-recirculation system, but provision of such a system will be easily accomplished through the fabrication of the appropriate porting.

b. Flue Gas-Water Heat Exchanger/Boiler

● Design Constraints

Both the shell-and-tube and finned-tube heat exchangers described above as primary and secondary approaches are designed. Two types of finned tubing - Escoa Turb-X and Wolverine continuous finned - are employed. Standard heat-exchanger-design methods are used to determine geometries for the initial prototype boilers.

The boilers are designed to attain an overall furnace efficiency greater than 80 percent at a thermal input of 100,000 Btu/hr.

● Design Choices

The shell-and-tube heat exchanger (the primary approach) is designed assuming a Nusselt number of 3.66; this conservative assumption will be checked during testing. A nominal tube-bundle diameter of 8 inches is chosen to facilitate adaptation to the CWS combustor; after choosing a tube outer diameter of 0.625 inch and a tube pitch of 0.825 inch, 85 tubes may be placed within the nominal bundle

diameter. A Nusselt number of 3.66 then yields a tube length of about 26 inches.

The continuously finned heat exchanger is designed of copper tubing with an outer diameter of 0.625 inch, a fin outer diameter of 1.5 inches, and a fin pitch of 8 per inch. Using standard design methodologies, it can be shown that a suitable boiler for the CWS furnace, made of finned tubing just described, should have about 5 rows of 4 tubes, each having a finned length of 9 inches.

Similarly, Escoa Turb-X finned tubing, with an outer diameter of 0.625 inch, a fin height of 0.375 inch, a 5/32-inch fin segment with a pitch of 4 per inch, is assembled into 9 rows, 4 tubes per row, and with 8 finned inches per tube.

c. Flue-Gas Cleanup System

● Design Constraints

A qualitative description of the performance requirements of the flue-gas-cleanup system has not been made and, in fact, is not within the scope of the current program. Thus, a qualitative measure of this system's performance is adopted - that it cleans the flue gas "adequately."

● Design Choices

The dry, bag-type cleanup system, which was adopted above, is designed. The initial prototype uses a mesh-sustained filter sheet dividing clean and dirty sections of a stainless-steel enclosure. This mesh will facilitate the laboratory evaluation of various filter materials.

2.3 TASK 1.50 - FABRICATION AND ASSEMBLY OF INITIAL PROTOTYPE COMPONENTS

Fabrication of the three components designed in Task 1.40 was nearly completed during this program period.

Three gas/water heat exchangers - one shell-and-tube and two different finned-tube models - were built and are being integrated into the Coal Combustion Laboratory. A bag-type flue-gas-cleanup system was fabricated and is also being installed in the laboratory.

A preliminary prototype combustor is under construction; it is anticipated that tests of this prototype combustor will simulate some operational characteristics of the IRIS combustor and will also allow testing of a complete flowtrain in the next program period.

Installation of the first prototype components of the CWS furnace - combustor, heat exchanger, flue-gas-cleanup system, and fuel-handling components - was underway during this program period and will be completed in the next period.

2.4 TASK 1.70 - TESTING AND DEVELOPMENT OF INITIAL PROTOTYPE COMPONENTS

Preliminary experimental study has verified certain key aspects of the design concepts. In particular, feasibility of the IRIS concept was proven experimentally.

Figure 2.7 shows a CWS flame spreading within a cylindrical chamber without any solids-detaining central partition. Air and CWS (atomized with a pressure atomizer) were introduced tangentially into this chamber, which had been preheated. Burning particles in this experiment formed a ring of flame which spread from the precombustor (formed here of firebrick) into a combustion area made of silicon carbide. It was noticed that gases left the combustion area carrying many partially burned particles.

The combustion situation improved dramatically when the two chambers were separated by a partition with a central opening (see Figure 2.8); the combustion chamber was temporarily removed here to illustrate combustion processes in the IRIS more clearly. The CWS flame was confined to the IRIS precombustor, and very few

Figure 2.7 Tangential CWS Flame in a Cylindrical Chamber

unburned particles were observed to leave the system. Here, atomized CWS was introduced tangentially into the IRIS, with cold combustion air.

Conditions during the experiment illustrated in Figure 2.8 are indicated below.

Estimated Thermal Input	100,000 Btu/hr
Estimated Heat-Release Rate in the Precombustor	570,000 Btu/hr/ft ³
Precombustor Diameter	8 in.
Precombustor Height	6 in.
Combustor Diameter	8 in.
Combustor Height	20 in.
Diameter of Opening in Central Partition	4 in.

The next step in the experimental part of the program will be testing of the three primary components in an integrated fashion. The fabricated systems of a CWS residential furnace will be integrated from the beginning. Further component development will occur with prototype components in isolation, but this first set of tests will provide an early emphasis on integration and manufacturability which will guide component development in the future.

The prototype combustor that will be tested has been designed to simulate some aspects of the operation of the IRIS combustor. Although the current device has been fabricated of ferrous materials (and so will not be allowed to operate at the temperatures anticipated to be necessary to meet program goals), the test program will verify certain conceptual assumptions allowing for final design of a (presumably ceramic) prototype IRIS. Also, various means of returning enthalpy to the evaporation zone will be examined during the testing of this hot-flow model and possibly a cold-flow model.

Figure 2.8 CWS Flame Confined in the IRIS
Precombustor Chamber

Two general types of heat exchangers were built: one shell-and-tube and two finned-tube versions. The more compact finned-tube heat exchangers will be favored if fouling does not occur; if finned surfaces are shown to be prone to fouling during the test program, the shell-and-tube heat exchanger will be selected.

The bag-type, gas-cleaning system will also be tested. The simplicity, low cost, and convenience of this system are quite attractive in a residential context, and testing of the prototype will allow for verification of the concept.

3. SUMMARY STATUS ASSESSMENT AND FORECAST

Figure 3.1 illustrates the progress to date; the program is ahead of schedule.

Tasks 1.30 and 1.40 were completed, and the preliminary component design package was developed. This package includes a novel furnace combustor concept as well as various heat exchanger and flue-gas cleaning subsystems.

Fabrication of the three components designed in Task 1.40 was 75 percent completed (Task 1.50).

Task 1.70, Testing and Development of Initial Prototype Components, will be the primary program focus during the next and following quarters. Primary goals of this testing will be:

1. Study the performance of the model combustor at the low temperatures allowable within the first prototype. Generate data useful in the design of the first IRIS.
2. Examine the fouling characteristics and heat-transfer performance of the heat-exchanger concept(s).
3. Verify the feasibility of the bag-type, flue-gas-cleanup system.
4. Integrate the components of a complete CWS furnace to gain practical experience to guide further development towards a practical, feasible and successful product.

Legend: Scheduled Actual

Figure 3.1 Status Chart

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