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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period January 22, 1987 - April 30, 1987

By
F.E. Becker, L.A. Smolensky, and M.A. McPeak

May 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 is the development of a coal-water-slurry (CWS) burning residential furnace. This report summarizes results of the first quarter of the first phase of the program effort carried out by Tecogen, Inc.

Overall furnace performance goals and specifications - the result of Task 1.10 - are detailed in Section 2.1 of this report.

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.

Figure 1.1 depicts the relationship among these components, as currently envisioned.

During the first quarter of effort, Tecogen, Inc., scheduled the completion of Tasks 1.10 (Design Criteria and Specifications Definition) and 1.20 (Literature Survey). Task 1.30, System Analysis, had been programed for initiation.

The program was substantially ahead of schedule at the end of the first quarter: Tasks 1.10, 1.20, and 1.60 (Laboratory Facility Modifications) were completed, and Tasks 1.30 and 1.40 (Component Analysis and Design) were begun. The experimental testing of prototype components, Task 1.70, was planned to take place in the fourth, and subsequent, quarters; however, to verify certain critical concepts, this task was started in the first quarter. Preliminary testing of some prototypical components was carried out.

Figure 1.1 CWS-Fired Heating System Flow Diagram

2. WORK PERFORMED DURING THE FIRST QUARTER

2.1 TASK 1.10 - DESIGN CRITERIA AND SPECIFICATIONS DEFINITION

2.1.1 Overall Requirements of the CWS-Fired Warm-Air Residential-Heating System

Overall design criteria and performance goals for the furnace are:

- Fuel CWS as primary fuel and No. 2 heating oil as secondary fuel
- Thermal Input 100,000 Btu/hr
- 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
- Turndown Ratio Greater than 3:1
- Service Life Greater than 20 years

The furnace will be capable of a 70°F reheat of about 800 cfm of air. An integrated ash-accumulation and collection system is also required.

A reasonably priced furnace with the above design criteria should be acceptable to potential manufacturers and users. Therefore, these criteria are adopted as goals for Tecogen, Inc. In order to attain these goals, new design concepts will be developed.

2.1.2 Component Requirements

a. Components Directly Related to Combustion Processes

In order to achieve a combustion efficiency exceeding 99 percent in a compact furnace, very high-heat-release rates are required. A rate of $200,000 \text{ Btu/hr-ft}^3$ is desired (in order to meet the size constraint outlined above). This is one of the most challenging technical problems to be addressed.

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; 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 larger than 50 to 60 microns will not have sufficient residence time for complete combustion.

Currently, the 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 excessively large appliance.

In order to accomplish our goals, achieve heat-release rates of $200,000 \text{ Btu/hr-ft}^3$ and high carbon-conversion efficiencies without solids recirculation, furnace components have to be designed in such a way that relatively coarse droplets (say, larger than 50 to 60 microns), will not be allowed to enter or will be detained in the combustion chamber. Developing and utilizing very effective atomizers and perhaps special aerodynamic schemes are required for these purposes.

An ultrasonic atomizer will be considered as the primary CWS atomization method. Besides the fine atomization and uniform spray,

which ultrasonic atomizers permit, easy scaledown to the 100,000 Btu/hr size is envisioned. Other types of atomizers will also be considered.

The atomizer is seemingly the most critical and important item in the furnace. However, an effective recirculation system in the combustor with internal recirculation of larger-diameter droplets might improve carbon conversion, flame stability, and relax atomization requirements. Therefore, the design criteria and technical requirements of the individual components of the combustion system and of the circulation system are interdependent. To design an inexpensive and thermally effective residential furnace, a reasonable compromise between furnace component requirements and circulation system complexity will be found.

The precise characteristics of the CWS fuel to be utilized will also affect furnace components. Slurry fly-ash loading will certainly relate to gas-cleanup system requirements and the CWS coal-particle size distribution will definitely affect atomization performance. It is convenient to require the CWS to be composed of finely micronized, beneficiated coal, water, and additives. Precise slurry specifications (including both component definitions and required rheology) will be generated during Task 1.30 from a systems standpoint, and Tasks 1.40 and 1.70 as affecting actual component design.

b. The Heat Exchanger/Boiler

The heat exchanger/boiler provides a mechanism for the transfer of heat from hot gases produced in the CWS combustor to a water loop. This circulating loop, in turn, heats air which warms the residence. After specifying, then, the rate of heat transfer from the combustion gases to the hydronic loop (based on a 100,000-Btu/hr thermal input), the fundamental heat exchanger/boiler design criterion will have been defined.

Now, the overall furnace design criteria reviewed above must be applied to the heat exchanger/boiler. The choice of CWS as the primary fuel, along with the desire for infrequent maintenance and high reliability, certainly requires the evaluation of potential fouling of boiler heat-exchange surfaces. A compact furnace size will mandate the efficient utilization of space within each component. High thermal output efficiency will demand a good heat-exchanger effectiveness of the boiler as well as reasonable pressure drops on both the gas and hydronic-loop sides of the device. The impact of the desired system turndown ability on the boiler must also be evaluated.

Concern about erosion and corrosion of heat-exchange surfaces will have a significant impact on, if not determine, gas velocities and temperatures around the boiler.

c. The Gas-Cleanup System

The primary purpose of the gas-cleanup system 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. However, these gases will contain both fly ash and some unburned carbon; 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.

Flue gases will be required to meet applicable environmental standards.

While the solids will be extracted from the flue gases, the recovery of additional energy from the gases may be worthwhile.

Clearly the gas-cleanup system is an integral part of the furnace and thus its performance affects other furnace components. For

example, any pressure drop encountered through the cleanup system will have to be accounted for in the design of the combustion-air fan. Compact size, long life, and low maintenance must also be considered.

Although cyclone and venturi scrubbers are often used in industry for such purposes, the high pressure drop required may not be practical for residential systems. Other possible systems, such as bag filters and water spray, should be evaluated.

2.2 TASK 1.20- REVIEW OF TECHNICAL LITERATURE

A literature survey has been carried out to gather information relevant to the CWS-Fired Residential Warm-Air Furnace program. A summary of some of the results of the survey is presented below.

2.2.1 CWS Rheology

a. General Rheological Behavior

At a very qualitative level, CWS rheology could be described as pseudoplastic or Bingham plastic with or without a yield point at zero stress. Also, speaking very generally, one could say that for a given slurry, viscosity can be manipulated through alterations in slurry temperature or by dilution.

But a much more complicated rheology lurks behind these simple relationships; a relatively cold, concentrated slurry may exhibit more desirable rheological behavior than a much more dilute, preheated CWS.

It is, fundamentally, the interaction of coal particles in the slurry with each other and with their aqueous environment that determines CWS rheology. Thus, the parameters that are relevant to the study of CWS rheology are: coal type, particle-size distribution, and loading; slurry chemistry; and shear environment - shear rate, history, and circumstances.

A wide variety of rheological behavior was found (see Appendix A, References, 1-15, 17, 19, 21-23, 27, 29, 30, 32, 34, 35, 41, 43,

44, 55, 60, 64, 74, 80, 82, 83, 85-87, 99, 109, 110, 112, 113, 137, 140, 143, 159, 166). A single CWS can exhibit regions of Newtonian, pseudoplastic, and dilatant rheology, as well as both thixotropic and rheopectic time-dependent behavior (10). Change from thixotropic to rheopectic rheologies, and from dilatant to pseudoplastic behaviors are observed for the same slurry at different shear rates, slurry temperatures, and shear histories (26). Also, the precise constituents of the slurry clearly affect CWS rheology. CWS rheology is thus strongly dependent upon the precise constituents of the slurry-coal type and particle-size distribution, coal content, chemical additives - as well as the shear environment encountered (1-5, 8-11, 17, 19, 21-23, 27, 29, 30, 32, 34, 35, 41, 43, 44, 55, 60, 64, 74, 86, 99, 109, 110, 137, 166).

The majority of reports reviewed concluded that CWS time-independent behavior may be described as Bingham plastic, yield pseudoplastic, or pseudoplastic (4, 5, 11, 17, 21, 35, 41, 137). Early characterization work, however, is much more varied in its description of CWS rheology; it is believed that the desire for yield pseudoplastic or Bingham plastic rheology has resulted in the development of techniques that promote these behaviors. Thus, while early slurries were often found to exhibit unfavorable behavior, later reports indicate that CWS rheology may be favorably affected by altering coal loading, type, particle-size distribution, and CWS chemical environment (2, 3, 7, 10, 11, 14, 17, 19, 21, 29, 30, 43, 44, 64, 86, 109, 110).

While it has been observed that no precise relationship exists between slurry properties and coal loading (112), in general, CWS viscosity increases with coal concentration (1, 29). This implies that a viscous slurry may be diluted to a lower viscosity. Also, for a given slurry, viscosity is reduced with an increase in temperature (5, 21, 83).

b. Desirable Rheological Behavior

Desirable CWS behavior may be characterized as: high viscosity or yield at low shear rates (to promote slurry stability), and low viscosity at shear rates encountered during pumping and atomization (to reduce pumping difficulty and aid in atomization). (See below.) (6, 10)

c. Particle-Size Distribution

Coal particle-size distribution exerts a profound effect on CWS rheology (2, 3, 12, 14, 17, 19, 21, 29, 30, 86, 157). A polymodal size distribution, resulting in better packing efficiency, encourages pseudoplastic behavior (2, 3, 12, 19, 29, 30, 86, 140).

d. Coal Content

The type of coal employed affects CWS rheology, although disparate results are encountered in the literature (21, 43, 80, 99, 109, 110). High ash coal has resulted in less rheological time dependency, while cleaner coals could be more highly loaded at reasonable viscosities (80). However, another study reported no influence between coal ash content and viscosity (43). Bituminous coals can be loaded more densely in CWS than porous or sub-bituminous coals (32), and also showed lower yield points but higher and constant viscosities (10). Low-rank coals have higher yields and low viscosities at high shear (10). Lignite and sub-bituminous CWS at a coal concentration of 51 percent were very pourable and yield pseudoplastic (99). With the same preparation, the apparent viscosities of several CWS's are in close relation to the O/C ratio of the coal, especially to the content of reactive oxygen. A similar relation exists between apparent viscosity and maximum inherent moisture of coal - those coals with larger pore volume, small contact angle, and more fusinite produce CWS with high apparent viscosity and low fluidity (109). The more hydrophobic a coal, the higher concentrated CWS can be made (110).

e. Coal Loading

For a given slurry, viscosity tends to increase with coal loading (1, 3, 5).

f. Shear Environment

It is important to note the wide variety of shear-dependent rheology noted in the literature. As pointed out previously, all types of shear-dependent rheological behavior have been observed: Newtonian, shear-thinning and shear-thickening, rheopectic and thixotropic. This is due to the other factors outlined here - coal content and loading, particle-size distribution, as well as chemistry (4, 5, 8, 9, 13, 21, 22, 35, 74).

By suitably controlling these parameters, then, any shear- and time-dependent rheology may be obtained.

g. Chemistry

Since the rheology of CWS is so profoundly affected by the interaction of coal particles, a great deal of effort has been expended studying various additives to achieve desired qualities (2, 6, 17, 19, 20, 21, 23-25, 27, 30, 33, 35, 41, 43, 44, 62, 63, 81, 83, 111, 112, 119, 140, 158, 160).

The viscosity of a CWS can be minimized by maximizing the natural repulsive forces between coal particles; this can be done by increasing zeta potential and surface hydrophilicity (2, 19, 43).

Many surfactants have been experimented with (17, 20, 21, 23-25, 27). The quantity of surfactant adsorbed on the surface of the coal particle is crucial, with surfactants yielding thick layers aiding dispersion and low viscosity (63, 83).

h. Pumping Systems

The pumping of CWS may be characterized as difficult. Not only is the pumped fluid corrosive, erosive, and prone to settling and pipe

blockage, but the shear rates found in many pumps have a degrading effect on the slurry, primarily by spoiling the chemical additives.

Thus research has been carried out both to study the pumping characteristics of CWS and to identify or develop components appropriate for use with slurry (5, 9, 37, 38, 55, 73, 77, 78, 108, 134, 135, 141, 143, 144, 154, 158, 166, 167).

The pumps that have been used successfully with CWS are mainly of the progressing-cavity type. These screw pumps are positive displacement and can be made with components that discourage erosion or corrosion. Also, the shear rates imparted on the CWS while passing through this type of pump, known by trade names such as Moyno or Ramoy, are quite low and therefore do not tend to degrade slurry additives (9, 37, 78, 141).

Erosion in CWS piping systems can be reduced by avoiding impingement, lowering particle top size, and by lowering the amount of hard constituents in the base coal (38). Laminar flow is found in CWS piping systems (5).

Flowmeters utilizing coriolis acceleration to directly measure mass flow, such as the Micro Motion units, have been successfully employed in CWS systems (145).

2.2.2 CWS Atomization

A large number of experimental and analytical studies of CWS atomization were reviewed (11, 22, 27, 28, 31, 40, 45, 48, 49, 53, 58, 66, 69, 70, 72, 76, 89-95, 101, 102, 104, 107, 112, 115-188, 129, 130, 139, 151).

Good atomization is of crucial importance to CWS combustion efficiency (26, 27, 45, 69, 89, 94, 101, 116, 122, 127, 130). As a result, atomization of CWS has been the subject of a great deal of study. The effect of atomization on combustion efficiency will be reviewed

below, while here the various atomization methods tried in the past will be reviewed.

The great bulk of reported work with CWS involved twin-fluid atomization (26, 27, 40, 49, 53, 70, 72, 76, 90, 92, 102, 104, 107, 115, 117, 127, 129). Mass mean diameters of less than 100 microns were achieved, though this varied widely, with various twin-fluid atomizers such as Y-jet, external-mixing, internal-mixing, and T-jet types. In general, the firing rates of the nozzles in question were above 1 million Btu per hour. The flow rates of slurry in these applications were such that the minimum flow areas encountered in the twin-fluid atomizers used were large enough to avoid plugging. The scaling of these atomizers to smaller applications would seem to present some technical challenge.

Nozzle shear rates in typical twin-fluid atomizers were around $50,000 \text{ sec}^{-1}$. This extreme shear environment makes the relevance of normal rheological studies, done at much lower shear rates, quite questionable.

With a twin-fluid atomizer, initial breakup of the slurry is via ligament formation. Secondary shattering of the CWS ligaments is due to air impingement (90).

Rotating-cup (10) and ultrasonic (16, 17, 53) atomizers were also used with CWS, and gave mixed results. The two references to ultrasonic atomization at flow rates near one gallon per hour were encouraging (16, 17).

A clear trend in the literature indicates that lower viscosity promotes better atomization (26, 130). But low viscosity is not the entire story: surface tension and slurry rheology are also extremely important (22, 90). Various anti-erosion measures have been taken to improve nozzle life while firing CWS. Pressure atomizers cannot handle high viscosity fluids, and so are not applicable to CWS (76).

With one exception it was pointed out that agglomeration of coal particles in a relatively large water droplet negated any advantage gained in finely micronizing the coal (58, 116).

2.2.3 CWS Combustion

A great deal of experimental and analytical work has been done to characterize the combustion of CWS, a portion of which was reviewed here (27, 36, 39, 42, 45-47, 49-54, 56-61, 65-72, 75, 76, 79, 88, 91, 93-98, 100-107, 117, 118, 120-133, 146, 152).

a. Modeling

CWS combustion was found to comprise four stages: water vaporization, coal devolatilization, volatile burnout, and coke combustion (47, 120, 121, 131, 152). More detailed stages might include: injection of CWS droplet, agglomeration during drying of droplet, localized ignition and ignition spreading, volatile flame formation, particle rotation, extinction of volatile flame and char ignition, fragmentation, and ash shedding and completion of char burnout (120). Each stage was studied empirically and theoretically, with various kinetic models presented and checked against laboratory data (146, 152).

The fundamental importance of CWS atomization to each of these combustion steps was emphasized.

b. Atomization

Atomization is the most important parameter affecting CWS combustion efficiency, turndown, ignition, flame stability, heat-release rate, and emissions characteristics (26, 27, 45, 47, 49, 58, 61, 69, 89, 93, 94, 101, 115, 117, 118, 122, 127, 130, 139, 165). Large droplets of CWS will contain several coal particles. During combustion, these particles will agglomerate and adversely affect slurry combustion.

The effect of poor atomization on CWS combustion can be examined in the context of the stages of slurry combustion. During the first

stage of slurry combustion, water evaporation, droplet drying times have been shown to increase exponentially with diameter (101). Thus the percent of total combustion time which is taken up by water evaporation is determined by the droplet size which in turn is determined by atomizer performance. In a similar manner, the mass-transfer and diffusion-limited processes of devolatilization, volatile burnout, and char combustion are strongly dependent on the surface area exposed to the process, and thus on the droplet diameter.

It has been shown that the combustion of the largest particles controls carbon-conversion efficiency (122). In the absence of any method of ensuring a longer residence time for larger particles, even a very small percentage of larger (say, 300 micron) particles will carry a relatively large amount of carbon up the flue.

c. Ignition

The heat required to evaporate the water in CWS represents less than 8 percent of the total heat liberated in combustion, and as such is of small import (26). However, ignition and turndown are significantly affected by this stage of CWS combustion (46, 163).

Clearly, ignition of a flow of CWS may not occur until and unless the water-evaporation stage has concluded. This explains why CWS flames are generally detached from the burner, beginning some distance after an oil flame would begin in a similar environment. Thus enthalpy must be supplied to the atomized CWS flow, either back from the high-temperature combustion zone or from some other source, to sustain ignition.

Ignition and combustion were strongly influenced by atomization (58). Because of agglomeration of coal particles in even the finest CWS spray, the very smallest fines which aid ignition in pulverized-coal combustion were not helpful.

d. Residence Time

The following data referent to the relationship among droplet residence time, diameter, and carbon burnout were found:

Reference	Particle Size	Residence Time	Carbon Burnout
51	Not Given	0.8-1.5 s	84-99%
58	100 micron	2.5 s	90%
59	70 micron	0.91-1.27 s	99.9+%
60	Not Given	100 ms	82-98%
69	44 micron	0.1-0.2 s	"Burnout Time"
95	10 micron	8 ms	"Burnout Time"
95	5-20 micron	35 ms	"Burnout Time"
126	50-100 micron	1 s	99.9+%

e. Carbon Burnout

Carbon burnouts ranging from 53 to 99.9+ percent were found (26, 50, 51, 56, 57, 59, 60, 70, 71, 75, 88, 97, 98, 107, 126-128, 147, 148, 150, 155, 164).

Burnout is related directly to residence time. The absolute residence time necessary to achieve a given carbon burnout is of course related to particle size (among other variables), which explains the fundamental importance of good atomization to high combustion efficiency (45, 61, 69, 89, 115, 117, 118, 122). Other important determinants of carbon conversion include mixing of combustion air with the slurry droplet (good mixing will reduce the residence time necessary to achieve high carbon burnout in a given droplet) (51, 57, 60, 71, 147), and preheating of slurry or combustion air (which reduces the time spent in vaporizing water from the droplet, thus hastening the combustion process so that more of a given residence time may be spent combusting char) (26, 53, 94, 161, 156).

f. Flame Stability and Turndown

Flame stability and turndown are promoted by many of the same measures important to good carbon conversion, such as fine atomization (45, 75, 89), reradiation of thermal energy back into the flame (50, 138), good mixing (65, 106, 156), preheat of slurry or air (65), staged combustion or a precombustion chamber of some sort (129, 132), and hot-gas recirculation (138). Also, an addition of enthalpy in the form of an assist fuel aids flame stability at a high turndown (46, 56, 156, 161).

g. Emissions

The amount of fly ash emitted after CWS combustion is primarily related to the carbon burnout achieved - poor carbon combustion results in a relatively large quantity of carbon going into the flue with the ash. This may augment the mass of fly ash to be processed considerably. Thus, clearly, residence time is the primary parameter determining fly-ash emission; all the variables influencing carbon conversion are then found to influence ash emission (26, 45, 49, 59, 98, 162).

NO_x production is found to be lower when combusting CWS than when burning the equivalent pulverized coal, because of the lower flame temperature produced with slurry (reported to be 2190°F) (26, 45, 49). Staged combustion of CWS has been shown to reduce NO_x production significantly (26, 102, 130, 139, 147-149, 162).

Practically all sulphur in the base coal is emitted in the form of SO_2 (26, 162).

h. Oxygen Enrichment

As might have been expected, oxygen enrichment improves all aspects of CWS combustion except cost (42, 94, 125, 133, 153).

i. Burner Development

Many CWS burners have been developed (26, 27, 45-47, 53, 59, 65, 70-72, 75, 76, 79, 97, 98, 101, 103-107, 117, 126, 127, 142, 147, 151) using various atomizers and many different flow schemes. In general, the characteristics desired for good combustion described above were promoted in the successful burners developed.

It was reported that the burner throat and air register should be designed with velocities comparable to coal burners, not liquid burners, and that the burner should have two airflow paths - a primary path low velocity rotating air and a secondary path air with high recirculation and high swirl (46). Combining these traits with a high radiant zone at the burner exit and a large igniter yielded a 3:1 turndown and good combustion efficiency (46).

j. Heat-Release Rates

Heat-release rates ranged from 18,700 Btu/hr-ft³ to 500,000 Btu/hr-ft³ (49, 57, 71). Techniques that promote a long residence time in a small volume (that is, low velocities) yield high heat-release rates.

2.2.4 Relation to CWS-Fired Residential Furnace

References to CWS combustion systems or components on the scale of the CWS-Fired Residential Warm-Air Furnace were rare. In general, while the rheological and basic combustion studies cited were clearly relevant, most atomizer and burner development focused on equipment on the utility or packaged-boiler scale.

a. Atomizer

It was clear that the application of pressure atomization to the current program would present profound technical difficulties. Since orifice plugging was a danger on the utility-boiler scale, the much smaller flow rates and correspondingly smaller orifice diameters needed

in the residential furnace would seem to rule out the use of pressure atomization.

Twin-fluid atomization might present fewer scaling difficulties than pressure atomization.

The introduction of moving parts into the slurry-combustion zone would seem to be risky, and thus rotating-cup or rotating-cone atomization has at least one potential disadvantage.

Ultrasonic atomization at present seems to be a quite feasible approach; flow rates on the order of those required in the residential furnace have been successfully atomized and combusted with various ultrasonic atomizers, and the droplet sizes produced were quite small.

b. Combustor

Approaches that resulted in good combustion in the larger CWS-firing efforts would seem to be quite applicable here. The use of staged-combustion, precombustion chambers, reradiation, and high swirl, among other techniques, will be studied to determine their relevance to the residential furnace.

c. Boiler

Though in many respects the boiler that will be developed in the current program will be conventional, past work studying the fouling of CWS-firing equipment will be utilized to ensure long heat-exchanger life and good efficiency.

2.3 TASK 1.30 - SYSTEMS ANALYSIS

Based upon the design criteria and performance specifications defined in Task 1.10, three conceptual design layouts of the CWS-Fired Furnace systems are being developed. Analysis of these concepts, which will be completed in May 1987, will identify areas of technical challenge, while a comparison of each layout will facilitate the

identification of initial priorities in the fabrication of prototype equipment.

The first design concept, which was described in Tecogen technical proposal No. TE2300-400, is shown in Figure 2.1. A vertical flow train is selected to minimize any ash or possible water build-up; the burner is fired vertically downward from the top and the ash collects at the bottom. To minimize the size of the boiler, combustion gases flow across the tubes to the outer shell; this shell is insulated on the outside to maintain its temperature above the vapor dew point at all times.

The flue gas, upon exiting the boiler section, is cleansed of particulates in a wet, impact-type scrubber and the ash residue is collected in a disposable plastic container. The scrubber also further cools the combustion gas and the heat is transferred back to the circulation air-stream for improved thermal efficiency.

Prior to the gas entering the wet scrubber, all metal surfaces in contact with the flue products are maintained above 250°F to minimize acid corrosion attack. While the dew point temperature is approximately 115°F, during startup and cooldown, corrosive condensate can form. Unless the metal surface goes above 212°F to quickly boil off the liquid, it can do appreciable damage. In fact, as the condensate evaporates, its acidity increases, making it extremely important that evaporation takes place quickly.

The temperature of the gas after it leaves the scrubber should be below 130°F to allow the use of PVC tubing. This type of tubing is commonly used in high-efficiency gas- and oil-fired furnaces. The important point in the design is not to end up with too low a flue temperature when metal surfaces are in contact with the gas, nor too high a temperature (after the scrubber) for the use of plastic pipe.

Figure 2.1 Coal-Water-Fired Furnace - First Concept

The scrubber-quench water goes to a plastic disposable container, lined with a charcoal impregnated filter paper. The filter will enable relatively clean water to be pumped to the secondary heat exchanger and, thereafter, to the water spray nozzles.

Very fine atomization is required for the first design concept: 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. The atomizer will be of an ultrasonic type (such as manufactured by Spraco, Inc., or Siemens, Inc.) for fine atomization.

The second design concept, Figure 2.2, avoids the necessity of fine atomization by restricting relatively coarse coal particles and CWS droplets (i.e., larger than 50 to 60 microns) from entering the combustion chamber. Because these larger particles are detained in the precombustion area, residence times are longer.

Concept 2 consists of a precombustor, combustor, flue-gas-water heat exchanger, and an ash collector. All components are placed within a water shroud recovering heat losses. The heat exchanger is similar to one used for the first concept while, in contrast to the first concept, cooled gases are cleaned by bag filters without water utilization.

Figure 2.3 depicts operation of the precombustion and combustion chambers. The primary-air inlet is directed tangentially into the precombustor, along with atomized CWS; alternatively, CWS droplets may be introduced axially through the center of the precombustor.

The precombustion and combustion chambers are separated by a partition with a central opening.

Although the precombustion chamber slightly increases design cost, some potential benefits of this combustion concept can be envisioned. In particular, the precombustion chamber:

Figure 2.2 Coal-Water-Fired Furnace - Second Concept

1. Atomizer	3. Combustor (Insulation Is Not Shown)
2. Precombustor (Insulation Is Not Shown)	4. Refractory

Figure 2.3 Precombustion and Combustion Chambers

1. Separates relatively coarse and fine droplets and provides selective retention of larger coal particles.

Centrifugal forces acting on the particles will not allow relatively large particles to leave the precombustion chamber until they are partially burned. Then, aerodynamic drag will overcome centrifugal forces and particles will leave the precombustor.

2. 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.

3. Evaporates water.

Precombustor temperatures will be high enough to promote intensive water evaporation and coal combustion. On the other hand, this temperature will be controlled below the ash fusion temperature and clearly below the temperature of thermal- NO_x formation.

4. Intensifies the processes of coal/air mixing.

As a result of this increased turbulence, combustion quality is improved.

5. 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.

6. Increases turndown ratio.

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

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

The third concept, shown in Figure 2.4, utilizes the same types of gas-cleanup system and combustor as Concept 2. However, it employs a tubular-type heat exchanger with vertical bare tubes, with flue gases inside the tubes and water outside. This type of heat exchanger has a higher likelihood of avoiding potential fouling and plugging problems.

Also, Concept 3 employs a cold-flow, cyclone-type separator, instead of a precombustion chamber, to prevent large coal particles 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 particles will proceed directly to the combustion chamber.

A preliminary comparative analysis of the three combustion concepts presented above indicates that the precombustor/combustor of Figure 2.2 has a high likelihood of technical success. Therefore, the combustion concept in Figure 2.2 can be considered as the primary focus of further development. Cold-flow models of the precombustor and combustor for this concept have been designed and will be fabricated and tested during the second quarter of work.

The basic combustion concept can be used in combination with the heat exchanger and gas-cleanup system shown in Figure 2.2, as well as in combination with the other components, for example, with the heat exchanger in Figure 2.4 and gas-cleanup system in Figure 2.1.

Figure 2.4 Coal-Water-Fired Furnace - Third Concept

2.4 TASK 1.40 - COMPONENT ANALYSIS AND DESIGN

Based on the results of Task 1.30, detailed analysis and design of the furnace components were begun in the first quarter, and will be completed in the second quarter. So far, design of the gas-cleanup system and heat exchanger shown in Figure 2.4 has been nearly completed.

Flue gases entering the heat exchanger have a rather high temperature; therefore, potential fouling and plugging of the heat exchanger must be considered. A tubular-type heat exchanger with vertical bare tubes, having flue gases inside the tubes and water outside, was designed. The heat exchanger cools the flue gases down to temperatures allowing for the use of bag filters; cleaned gases exiting the filtration area may be cooled further, perhaps using extended heat-transfer surfaces.

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

2.5 TASK 1.60 - LABORATORY FACILITY MODIFICATIONS

The residential heating system laboratory has been modified to enable bench testing of individual furnace components as well as of the completed furnace.

Lab modifications are based on Figure 2.5, laboratory layout, and Figure 2.6, CWS pumping schematic.

Figure 2.5 shows the lab layout. Stations are assigned to the development of various components of the CWS-Fired Warm-Air Heating system, and are centered around a flue and the CWS fuel-handling system. A special station is prepared where atomization studies may

Figure 2.5 Laboratory Layout

Figure 2.6 CWS Supply System

proceed. This atomization hood, already utilized for the ultrasonic-atomization, proof-of-concept test, will be used to test various atomization techniques.

An oil-ash mixture will be prepared to facilitate evaluation of the boiler and particulate-removal systems; a storage and pumping system are constructed for this mixture.

2.6 TASK 1.70 - TESTING AND DEVELOPMENT OF INITIAL PROTOTYPE COMPONENTS

The purpose of initiating the testing of some furnace components at this early stage of the program is to explore some preliminary concepts, verify various design assumptions, and prepare for full-scale testing.

A standard residential oil burner has been obtained and tested with oil. The burner has also been fitted with an ultrasonic nozzle and this system was tested. While facilitating testing of the CWS furnace components which are not specific to CWS firing, such as the heat exchanger and ash-collection systems, the burner also, as fitted with the ultrasonic atomizer, has allowed evaluation of the ultrasonic technique for slurry to proceed.

A SPRACO 50 liter/hour (water) ultrasonic atomizer was also tested. Encouraging results for CWS were obtained when CWS atomized by this device was slightly diluted or preheated to lower viscosity.

An off-the-shelf pressure atomization system, commonly used to atomize high-viscosity paints, was also tested with CWS; rather fine atomization was achieved. However, the atomized-slurry jet produced with the paint sprayer had very high momentum - a potential drawback.

CWS atomized with the pressure atomizer was burned in a preheated silicon-carbide-lined chamber. Best results were obtained when the CWS flow was introduced tangentially into the combustion chamber.

2.7 SUMMARY STATUS ASSESSMENT AND FORECAST

Figure 2.7 illustrates the progress to date; the program is ahead of schedule.

Tasks 1.10, 1.20, and 1.60 were completed. Based on the design criteria and performance specifications, three conceptual design layouts are being developed. The primary combustion-chamber concept has been identified as employing a precombustion chamber to provide selective retention of larger coal particles. Design of furnace components was begun, and preliminary designs of the heat-exchanger and gas-cleanup systems were advanced.

Tasks 1.30 and 1.40 will continue to be primary program focuses during the next quarter. To verify some principles relied upon in the combustor designs presented above, cold-flow models of the pre-combustor and combustor chambers will be fabricated and tested. Preliminary hot-flow testing will begin.

Legend: Scheduled
 Actual

Figure 2.7 Status Chart

APPENDIX A

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