TECHNICAL REPORT

March 1, 1992 through May 31, 1992

Project Title: Cooperative Research on the Combustion Characteristics of Cofired
Desulfurized Illinois Coal and Char with Natural Gas

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ABSTRACT

The objective of this project is to determine the contributions of coal type, sulfur type, temperature, and residence time on the coal combustion behavior (especially the effects on ash constituents) during cofiring with natural gas. The Drop Tube Furnace Facility (DTFF) at the University of Illinois at Urbana-Champaign (UIUC) is the chief apparatus to be used in this investigation, with additional diagnostic tools including scanning electron microscopy and other chemical analyses.

The DTFF was modified to extend the operating range to larger sample collection capabilities and higher temperatures. A plasma gas heater was designed and constructed so that temperatures and heating rates encountered by pulverized coal particles in the flames of large boilers or in the advanced slagging combustors are better simulated. A LECO Sulfur Determinator for total sulfur analysis was refurbished, and arrangements were made with the Illinois State Geological Survey for the analysis of char and ash at UIUC. The modified DTFF, referred to as the Ash Characterization Facility, has been set up and initial tests with ash collection and analysis have been performed. The plasma torch has been tested, and steady operation has been established.

In the current quarter, the Ash Characterization Facility has been used to produce ash samples from IBC 106 coal at several temperatures and residence times. The total sulfur in the ash samples has been determined, showing the contributions of methane cofiring for operating parameters. A long sampling probe has been constructed, which will enable ash and char samples to be obtained at various residence times. Preparatory work with the gas chromatograph has been initiated to permit the simultaneous analysis of both the gas phase with the solid particle. The plasma torch has been fully calibrated and the gas preheating system completed. Tests with the torch connected to the drop tube indicate that it is necessary to heat the entire tube to a high temperature if tests are to be performed at these temperatures.

In the next quarter, a more complete set of tests with varying residence times at several temperatures and methane concentrations will be run on the Ash Characterization Facility, and analyses will be made to see how the sulfur is transformed during the combustion process. The high temperature capability with the plasma torch will be further developed.

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EXECUTIVE SUMMARY

The reduction of sulfur emissions from the combustion of Illinois coal is very important and urgent. Research on the fundamental level can provide a better understanding of the processes involved in clean coal technologies, and offer basic data and new approaches for improving the present technology or developing new technologies. This project considers the effects of co-firing natural gas with Illinois high-sulfur coals to determine the sulfur retention potential as a function of sulfur content, sulfur type and natural gas concentration. Previous experimental results from UIUC have shown that co-firing natural gas and coal has the potential for reducing sulfur emissions by increasing sulfur retention in the ash. Additionally, other researchers have suggested that co-firing of natural gas and coal reduces ash deposition problems.

To study sulfur retention in ash and deposition problems, the mechanism and rate of sulfur and mineral transformation must be understood. A survey of literature shows that present works on sulfur transformation are mainly limited to pyrite, and the details of transformation in coal under boiler conditions are not well studied. Ash formation and behavior under boiler conditions have just begun to be studied in a fundamental way, and the range in conditions and the degree of quantification are still quite limited. The effects of high temperature on ash behavior such as those encountered in large boilers (~2000K) or slagging cyclone furnaces (~2000K) have not been studied for lack of a suitable apparatus. Also, the effect of natural gas co-firing has not been thoroughly investigated. Therefore, through the present project, we seek to obtain results contributing to the understanding of these subjects with the goal to find more effective ways to limit sulfur emission and to reduce boiler deposition.

The strategy of the present project is to use the Drop Tube Furnace Facility (DTFF) to create a controlled combustion environment representative of that in a real boiler furnace, and to follow the transformation of sulfur and minerals in coal through the combustion process under these controlled conditions. To achieve these objectives, the DTFF has been modified to enable larger ash samples to be collected in a relatively short time under the conditions of heating rate, temperature, residence time and gas composition comparable to those in the actual boiler furnace. A long silicon carbide tube of larger diameter is used to allow higher feedrate of coal and achieve longer residence times. Methane is added with the coal in various concentrations. Ash samples collected at various positions along the drop tube are analyzed for sulfur content and other mineral contents. Thus the transformation of sulfur and other elements can be studied. A plasma torch gas heater is to be used in the high-temperature, high-heating-rate tests for preheating the combustion gas to high temperatures.

The work in the first quarter consisted of the literature survey, exploring and defining the relationship between requirements of Clean Coal Technology, especially those directly affecting the use of Illinois coal, and the works of the present project, and setting up the strategy of the present project. With the desired range of parameters defined, the apparatus modification was initiated. A plasma torch gas heater was also designed and constructed.

In the second quarter, the modification of the DTFF was completed. The apparatus is now relocated in the Mechanical Engineering Laboratory. The furnace has a 35 mm (i.d.), 1.5 m long, silicon carbide tube which can be used to high temperatures. A continuous type coal feeder was developed. Preliminary runs with IBC106 coal with and without methane addition were made, and analyses of the collected ash with the LECO Sulfur Determinator showed results consistent with those previously obtained. The plasma torch was tested, and a set of conditions for steady running was established. Nitrogen stream of 4000K temperature was obtained.

In the current quarter, additional ash collecting tests were run. The main coal sample used was the IBC106. A temperature range from 1250K to 1750K and methane concentrations from 0 to 4% were investigated. Residence time of the order of 1 second was used. The results show various contribution of the methane co-firing and the effect of temperature. Generally, the level of sulfur retained in the ash was relatively low, probably due to the high temperatures and long residence times. Additional data showing the transformation process of sulfur in coal during combustion will be needed. The results of these tests are discussed in more detail in the third quarter TECHNICAL REPORT for the project entitled "Combustion of Illinois Coals and Chars with Natural Gas."

A long, water-cooled sampling probe has been constructed for collecting ash samples with a wider range of residence times. This probe can be inserted to various positions up to two-thirds of the length of the furnace. Together with the adjustment in the position of the coal injector and the variation of flow velocity, a wide variation of particle residence time can be investigated. Preparatory work has begun on the gas chromatograph (GC) for analysis of gaseous species containing sulfur, so that gas sample analysis may be carried out concurrently with the solid ash sampling. Additional coals have been ordered and are being prepared in the sizes required. Maintenance work was done on the Leco Sulfur Determinator.

The plasma torch gas heater has been completely calibrated over the intended range of operation. Steady, repeatable and trouble-free operation has been achieved. Tests on the drop tube indicate that the entire tube needs to be heated in order to conduct combustion tests at high temperatures. Thus modifications are necessary before the apparatus can be used for tests above 1750K with the plasma torch gas heater.

In the fourth quarter, systematic tests on various coals at several temperatures, including a wide range of residence times, will be carried out. The determination of the types of sulfur will be performed provided a sufficient quantity of ash samples can be collected. Such experiments will provide insight into the sulfur transformation mechanisms. The plasma torch gas heater will be tested on a high temperature drop tube arrangement to investigate combustion environment up to 1700°C (1973K).

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OBJECTIVES

The overall objective of the project is to determine the effects of treatment processes and natural gas co-firing on the ash characteristics for Illinois coal, with the intent of finding better methods of reducing the sulfur emission and ash deposition problems. In order to achieve this objective, it is necessary to make detailed studies of sulfur and mineral transformation during combustion and behavior of ash under various conditions for parent and treated coals.

The specific objectives for the current year are to obtain sulfur and mineral transformation data under well controlled conditions in the Drop Tube Furnace Facility (DTFF) for two Illinois coals (high pyritic and high organic sulfur) and their treated products, with and without natural gas co-firing, thereby gaining an understanding of the mechanism and potential in reducing the sulfur emission and ash deposition problems. Each set of data will consist of a number of data points taken at various residence times under identical conditions of gas temperature, composition and flow velocity.

The tasks to be completed in order to meet the objectives are the following:

1. Formulation of the complete strategy, methodology and outline for this research combined with initial ash characterization experiments. (1st quarter)
2. Modification of the experimental apparatus and methods of analysis. (1st - 2nd quarter)
3. Refine the apparatus and perform further experiments. (2nd quarter)
4. Running of the experiments to obtain a series of reliable data. (2nd - 4th quarter)
5. Analysis of the data to arrive at an assessment of the effects of the various factors and an understanding of the processes involved. (4th quarter)
6. Project completion and recommendations for future work. (4th quarter)

At the end of the third quarter, the tasks are being performed as indicated above. Instrument breakdowns, lack of equipment inventory, and delays in the preparation of coal samples have resulted in slower progress than anticipated. However, tasks 4, 5 and 6 will be completed at the end of the fourth quarter.

INTRODUCTION AND BACKGROUND

There are many significant research issues impacting the use of our coal resources including the mechanisms of pollutant emission and methods of pollution control, methods to achieve stable and efficient combustion, mineral matter transformation which mainly affects slagging and fouling in boilers, combustion modeling, database on fuels and combustion characteristics, diagnostic methods, etc. At present, the environmental requirements as exemplified by the Clean Air Act Amendment of 1990 pose an important and urgent problem for the coal producers and users, especially to the state of Illinois. Due to the high sulfur content of the Illinois coals, many users may switch to low-sulfur coals in order to comply with the standards. There will be significant losses of markets and jobs. Therefore it is of utmost importance and urgency to find better solutions to the sulfur pollution problems in the combustion of Illinois coal.

Illinois is actively involved in many of the clean coal research and demonstration projects. For instance, the Gas Reburning and Sorbent Injection project has started at Hennepin and Springfield. The Low NOX/SOX Burner for Utility Cyclone Boilers project is being carried out at Marion. The demonstration project of Mild Gasification of Illinois Coal has started at the Illinois Coal Development Park. Research on a fundamental level is also being supported. This fundamental research provides a better understanding of the processes involved in the clean coal technologies and offers basic data and new ideas to the pilot or industrial scale studies with the purpose of improving the present technology or developing new technologies.

UIUC has been performing basic research in coal combustion for many years. One of the most recent projects has been the study of combustion characteristics of desulfurized Illinois coal and char. An Entrained Dust Flow Facility (EDFF) and a Drop Tube Furnace Facility (DTFF) have been used to study the ignition, flame speed and emission characteristics of parent and treated Illinois coals. The DTFF provides the capability to study single particle combustion with simultaneous measurements of particle temperature, morphology and velocity of the coal. The effects of natural gas co-firing have been studied, and it was found that co-firing decreases ignition delay time for low volatile coals or chars. It was also found that addition of natural gas increased sulfur retention in the ash, so the reduction in sulfur emission could be more than the simple displacement by natural gas.

The availability of the DTFF as a research tool for accurately controlling the environment of coal particle combustion and the possibility of increased sulfur retention in ash make further study into the details of sulfur transformation an important next step. Since ash deposition is a major problem with boiler operation, ash behavior under conditions simulating the actual boiler is also worth studying. Therefore the DTFF is used to further study of sulfur and mineral transformation as affected by coal type, treatment methods and natural gas co-firing.

The results of this research project will provide a better understanding on how sulfur and minerals are transformed in combustion and how the coal type, treatment methods and natural gas co-firing affect these transformations. Thus better methods of reducing sulfur emission and ash deposition problems may be found.

The original DTFF at UIUC was designed to obtain accurate *in situ* diagnostic data on individual coal particles during transit through the drop tube. It was not convenient to use the original furnace for gathering large amounts of ash in a short period of time. Also the temperature and heating rates of the original DTFF did not simulate the conditions in the

hottest flames of large boilers or in the advanced slagging cyclone combustors. Therefore, the DTFF was modified to become an apparatus more convenient for ash studies and collection, with high temperature capabilities encountered in large modern boilers.

EXPERIMENTAL PROCEDURES

The emphasis of this project is on the transformation of sulfur under conditions representing those in the actual furnace, the mechanisms of ash formation at high temperatures, and the effects of natural gas co-firing on these processes. To study sulfur retention in ash, the mechanism and rate of sulfur transformation must be better understood. The selected experimental technique is to heat coal particles in a drop tube furnace at boiler heating rates (10^4 ~ 10^5 K/s), temperatures (1250~2000 K) and residence times (tens of milliseconds to the order of seconds). The samples are quenched and collected for observation and analysis.

The modified drop tube furnace, referred to as the Ash Characterization Facility, has a silicon carbide tube, 35mm i.d. and 1.5m long. It is heated by Kanthal Super-33 heating elements made of molybdenum disilicide, mounted inside the furnace chamber with firebrick insulation. This tube permits a larger flow rate of coal with longer residence times. Coal particles are injected with a continuous screw-type feeder into the high temperature gas to achieve high heating rates. A sizable ash sample can now be obtained in a matter of minutes.

The sampling probe consists of four concentric thin-walled stainless steel tubes. The outer three form the cooling water jacket and the inner one supplies a stream of helium quench gas. The helium is injected near the tip of the probe to quench the reaction of the particles entering the opening. A vacuum pump draws the gas through the probe, and ash samples are collected in the stainless steel gauze filter near the probe tip and also on the filter paper at the bottom.

The ash samples are analyzed for total sulfur in the laboratory with the LECO Sulfur Determinator. This instrument uses a high temperature furnace with oxygen gas to burn out all the sulfur in the sample. Infrared absorption in the instrument test cell provides the resulting sulfur dioxide. This instrument is very sensitive and accurate even with a few milligrams of sample. However, the high temperature ceramic tube in the instrument is prone to failure if the furnace is cooled down too rapidly and too often. The other elements are analyzed by the Illinois State Geological Survey (ISGS). Silicon is used as a tracer to calculate the material balance, assuming that it is kept in the coal ash without evaporation throughout the combustion process.

The variables in these experiments are coal type, furnace temperature, oxygen concentration, methane concentration and residence time. Residence time is controlled by the flow velocity and the distance from the point of coal injection to the sampling probe. The details of the experimental methods for these ash collecting tests are given in the quarterly TECHNICAL REPORT for the project entitled "Combustion of Illinois Coals and Chars with Natural Gas." When reliable data are obtained as a function of these variables, the sulfur transformation mechanisms can be assessed and comparisons with model predictions are possible.

For preheating the gas to high temperatures, a plasma torch gas heater has been designed, constructed and tested. The details of this system and test results are given in the APPENDIX of this report.

RESULTS AND DISCUSSION

Work Performed During the Third Quarter

In this current reporting period (March 1, 1992 to May 31, 1992), the following tasks have been performed:

1. Sulfur Retention in Ash for IBC106 Coal

Ash collection experiments with IBC106 coal with and without methane addition have been performed in the Ash Characterization Facility. These experiments included temperatures of 1250, 1500 and 1750K; methane concentrations of 0, 2 and 4%; and gas velocities of 1 and 1.75 m/s. The sampling probe was located near the outlet of the furnace. The results of the tests are given in the quarterly TECHNICAL REPORT for the project entitled "Combustion of Illinois Coals and Chars with Natural Gas." Although some of the results need to be reevaluated, the level of sulfur retained in the ash is, on the whole, relatively low. This may be the result of long residence times and high temperatures experienced by the particles. To clarify these results, it is necessary to perform additional experiments at the above conditions as well as at various residence times during the combustion process. The variable residence time experiments can be accomplished with the long sampling probe.

2. Preparatory Work for More Detailed Experiments

In order to take samples at various residence times, a long sampling probe was constructed. It consists of four concentric stainless steel thin-walled tubes welded into an outer cooling water jacket and an inner sampling passage. Provisions for helium quenching gas injection near the probe tip have been incorporated into design. Cooling water at 1.1 MPa was used to keep the probe cool when it is completely inserted into the furnace. The heating flux from the drop tube to the sampling probe was about 4 W/cm² based on the probe surface at a furnace temperature of 1250K. When inserted into the drop tube, the probe absorbs energy from the tube so that the tube temperature is reduced by close to 100°C. The probe can be positioned to a point 0.94 m into the drop tube (from the bottom). Also, the coal injection tube can be lowered into the drop tube from the top to obtain very short residence times.

The gas chromatograph (GC) is being prepared for analyzing the sulfur-containing compounds in the gas phase. A gas sampling valve has been installed in the furnace volume of the GC so that the quantitative analysis of the low concentration gases is now possible. Simultaneous solid particle and gas sampling in the drop tube will provide insight into the mechanisms of sulfur transformation during combustion.

3. Calibration of the Plasma Torch Gas Heater and Trial on the Drop Tube

The plasma torch gas heater has been calibrated over the useful range of operation. The torch can be run on pure nitrogen to produce a gas stream with temperature from 1500K to 4500K at suitable flow rates. The operation is reliable, simple and steady. A detailed summary of the system and the calibration results are given in the APPENDIX.

The plasma torch was connected to the drop tube and initial tests were performed. The silicon carbide tube handled the hot nitrogen and no cracking was observed. Gas temperatures up to 2000K were measured at the entrance to the cold furnace. However, it was realized that the gas from the plasma torch was much hotter than 2000K and it was rapidly cooled down by the colder walls of the tube. Calculations showed that even if the wall was only a few hundred degrees cooler than the gas, the temperature of the gas would approach that of the wall in a relatively short distance. Therefore, in order to test under high temperature conditions, the drop tube must be heated to the desired temperature and the plasma torch will act as a gas preheater.

Work Scheduled for the Fourth Quarter

A series of ash characterization experiments will be performed during the fourth quarter. The variable to be investigated are temperature, methane concentration, residence time, and coal type. An important element of these experiments, as compared to those in the third quarter, will be the coverage of a wide range of residence times. Also, larger quantities of ash sample will be collected to enable the analysis of the types of sulfur. These data will provide insight into the mechanisms of sulfur transformations and effects of natural gas co-firing.

The high temperature capability of the drop tube furnace will be developed through enhanced tube heating and insulation and with plasma torch preheating. A tube and gas temperature in the test section of 1700°C is the target.

CONCLUSIONS AND RECOMMENDATIONS

To study the sulfur retention in ash as well as ash deposition problems, the mechanisms and rates of sulfur and mineral transformations must be understood. Our literature survey shows that present works on sulfur transformations are mainly limited to pyrite, and the details of the transformations in coal under boiler conditions have not been thoroughly investigated. Basic studies in ash formation and behavior are also limited. Therefore, we seek to obtain a more comprehensive understanding of these subjects with the goal to find more effective ways to limit sulfur emission and to reduce boiler deposition.

Experiments have been performed in the Ash Characterization Facility during the current quarter. Results show that there is sulfur leveraging in the ash due to methane co-firing, but the sulfur levels are low and strongly dependent upon temperature. To obtain more conclusive results and an explanation of the governing mechanisms, more experiments with a wider variation in residence times are needed. These tests will be made in the fourth quarter.

The plasma torch gas heater can satisfactorily provide high temperature preheating gas. To make combustion tests at high temperatures, the drop tube must be enhanced through additional heating and insulation. An arrangement to operate at high temperatures with the plasma torch is being made, and the results will be obtained in the fourth quarter.

APPENDIX: THE PLASMA TORCH GAS HEATER

Introduction

In scientific research and industry, there are needs for continuous gas streams at temperatures of a few thousand Kelvin, which are not easily reached by ordinary heating methods. Plasma generators can provide such gases quite conveniently, and can be used in many cases.

In the drop tube furnace for coal combustion studies, the gas needs to be preheated before it enters the tube so that the coal particles will enter a hot environment as soon as they leave the injector. In this way, high heating rates simulating those in the real boiler furnace may be achieved. Furnace type preheaters have often been used (e.g., reference [1]). Plasma heaters, either using the arc [2,3] or high frequency induction [4], have been used to preheat argon gas as an inert in drop tube furnaces. Although the plasma preheaters can heat gases to high temperatures, the gas temperature in the test section soon reaches that of the surrounding tube due to heat loss to the wall. Thus the reported test data were all limited to the tube temperature. In reference [2], although a gas temperature of 2000K was reached, the reported data were only given up to 1750K. In reference [3], a graphite tube heated by graphite elements was used, and arc heated argon gas was injected (no oxygen). The temperature reached was 2100K for devolatilization studies at high temperatures.

In reference [5], the authors studied high particle temperature combustion of pulverized coal in high oxygen concentration gases. The furnace used did not have a heated tube, and the gas was preheated and entered the furnace with direct radiation heating by the walls and the LaCrO_3 heating elements. The gas temperature reached 1600°C (1873K) in the tests.

The aim of the present work is to study sulfur and mineral transformations in coal under controlled conditions simulating real boiler furnaces. In large boilers and cyclone furnaces, flame temperature can reach 1700°C or even higher. Thus it is desirable to be able to test coal combustion at these high gas temperatures. However, due to limitations in heating and in insulating materials, most furnaces are limited to temperatures below 1500°C. A 100°C increase at such temperature levels is not easily achieved. At present, 1700°C furnace technologies are available (e.g. see reference [6]), and plasma gas heaters can readily produce high temperature gases. So it is reasonable to expect that high-temperature drop-tube furnaces operating at 1700°C (1973K) are possible.

Assuming that nitrogen gas at 2000K is flowing down the tube with a velocity of 1 to 2 m/s, the flow rates required for two different sized tubes are as follows (specific volume of nitrogen at 2000K and 0.1 MPa is 5.937 m³/kg):

<u>Tube diameter</u>	<u>Velocity</u>		
	<u>1 m/s</u>	<u>1.5 m/s</u>	<u>2 m/s</u>
35 mm	0.162 g/s	0.243 g/s	0.324 g/s
50 mm	0.331 g/s	0.497 g/s	0.662 g/s

A gas preheater capable of providing such gas flows has been constructed. A d.c. arc plasma torch has been designed to give steady and repeatable performance, to be free from operational and maintenance problems, and to operate easily. Test results show that these requirements have been well met.

Design of the Plasma Torch

The drawings of the plasma torch is given in the following section. The torch contains a thermionic cathode, a gas swirl chamber and a stepped anode. The cathode is a small thoriated tungsten rod embedded in a water-cooled copper tip. This enables the tungsten rod to be well-cooled on the sides and limits the arc root to the center of the rod. The erosion of the cathode in non-oxidizing atmosphere is kept to very low values, and the life under the present operating conditions ($I < 50\text{A}$, 1 atm, N_2) can be hundreds of hours.

The anode is made of copper, water cooled. The arc is drawn through the throat by the action of the swirling gas, and attaches to the enlarged passage downstream. The point of attachment of the arc depends on the gas flow rate, the arc current, and the amount of swirl. However, the attachment point will not go beyond the exit plane of the anode, thus limiting the arc length and the arc voltage. The gas swirl tends to rotate the arc root around the periphery of the anode passage, but due to the small current with the accompanying small diameter of the arc column, the aerodynamic force is not large enough to rotate the arc root evenly all the way around the periphery but only covers part of the circular path. At the present conditions of operation, there is no evident sign of serious erosion, and the anode should last for several hundred hours of operation. The gas injection ring has one tangential hole to produce a swirling gas necessary for stabilizing the arc on the axis. Sealing of the gas injection ring in the torch body is achieved by using paper gaskets at both ends of the ring. The number of holes (one) was arrived at through experimentation for best effect on arc stabilization.

The arc is started by a high-frequency, high-voltage discharge provided by the power supply. Once the gas breakdown occurs in the gas between the electrodes, arc current flows through the gap and the arc is formed. It is immediately swept into the final configuration by the aerodynamic action of the blowing gas. A mechanical contact starter consisting of a spring-loaded tungsten rod and actuated by a solenoid-lever system was also successfully employed to start the arc. It can be used if the power supply does not have the high-frequency, high-voltage starting circuitry.

Nitrogen is used as the working gas of the plasma torch and a mixing section is provided for mixing in oxygen or other gases downstream of the torch exit. This is done because it is necessary to have the composition of the gas in the drop tube furnace closely simulating the furnace gas environment in the actual boiler. It is more difficult to run the plasma torch on nitrogen than on argon because of the differences in thermodynamic and transport properties of the two gases. In fact, all the other investigators who used plasma heating for coal studies used argon as the main working gas. With suitable design of the torch and a suitable power supply, steady and continuous running on pure nitrogen has been achieved in the present plasma torch.

The power supply used for this plasma torch is a plasma cutting power unit of the inverter design (L-TEC PCM82i). This type of power supply gives high output voltage (open circuit voltage 280V, rated output voltage 120V) at low current (10-80A, 50A continuous), which is suitable for this torch running on pure nitrogen. The inverter design is a new development in plasma cutting power supplies. It features a rectifier, an inverter which produces a high frequency a.c. current with feedback control, and a final rectifier which provides the output d.c. current. Since the inverter works at high frequency with a sensitive feedback circuit, the power supply is very compact (only 285 mmW x 485 mmH x 515 mmD, weighing 44 kg), and the current control is fast responding and accurate.

Gas from cylinders is metered through rotameters. Circulating cooling water is provided by a gear pump through proper filters. Water pressure of about 0.3 MPa (~45 psig) is used.

Drawing of the Plasma Torch

Figure 1. Schematic of Plasma Torch

Calibration and Performance of the Plasma Torch

Since the gas jet has a temperature of a few thousand Kelvin, thermocouples cannot be used for temperature measurement. The average temperature of the gas jet is obtained by energy balance and using equilibrium thermodynamic properties. The torch and mixing section were tested as one unit, so the temperatures and efficiencies given are those at the exit of the mixing section. The arrangement for calibration was either of the two shown below:

1. Calibration Arrangement 1.

From the energy equation,

$$\dot{m}_g (h_2 - h_1) = U I - \dot{m}_{H_2O} c_p \Delta T$$

where

h_2 = enthalpy of exit gas (hot),
 h_1 = enthalpy of inlet gas (cold),
 U, I = arc voltage and current, respectively,
 $\dot{m}_{H_2O}$ = flow rate of cooling water,
 $\dot{m}_g$ = flow rate of working gas,
 ΔT = temperature rise of cooling water, and
 c_p = specific heat of water.

Thus, h_2 can be calculated from the measured values of $U, I, \dot{m}_{H_2O}, \dot{m}_g, \Delta T$, and known thermodynamic data. T_2 is obtained from the h - T data of the gas.

Thermal efficiency of the system is defined as

$$\eta = [(\dot{m}_g h_2 - \dot{m}_g h_1)] / (UI) = 1 - (\dot{m}_{H_2O} c_p \Delta T) / (UI)$$

It can be seen that if the efficiency is low (i.e. heat loss is a large part of UI), the percentage error in temperature and efficiency will be larger.

2. Calibration Arrangement 2.

In the second arrangement, a calorimeter is connected to the exit of the mixing section and cools down the gas to a low exit temperature T_e . This temperature can be measured by a thermocouple. The energy equation for the calorimeter is:

$$\dot{m}_g h_2 - \dot{m}_{H_2O} c_p \Delta T = \dot{m}_g h_e$$

or

$$h_2 = h_e + (\dot{m}_{H_2O} c_p \Delta T) / \dot{m}_g$$

and T_2 is obtained from h_2 .

This arrangement gives better accuracy especially at low efficiencies. The water flow through the calorimeter should be steady and adjusted to give a good reading of ΔT .

In the present work, both arrangements have been tested, and comparable accuracies have been obtained. The data presented here were obtained with arrangement 1.

A set of performance data for the plasma torch with the mixing section attached (but no gas mixed in) is shown in Fig. 2. These data can be used in selecting the setting of the plasma torch. When additional gases are mixed in, the temperature is lowered, as shown in Fig. 3. The arc voltage values are for a given position of the cathode relative to the anode. If this position is adjusted, higher or lower arc voltage will result.

It can be seen from these data that high temperature gas flows at the desired temperatures and flow rates can be readily obtained from the plasma torch. Operation of the torch is steady, can be continuous for many hours (or days, if necessary), and the power consumption is in the range of 1-3 kW. The equipments are of a manageable size. Other than the present application of preheating gas for the drop tube furnace, this plasma torch can be used in many applications where there are needs for high temperature gas streams.

Operating Procedures

1. Safety Precautions

The power supply has an open circuit voltage of 280V and the operating voltage with the arc may be 120V. Contact with these voltages may be lethal. Make sure that the cathode circuit is well insulated at all points.

The high temperature N_2 will form harmful nitric oxides when in contact with air. The exhaust gases should be vented when testing in the open jet mode.

The noise from the open jet can be harmful to the ear, especially at higher power levels. Protective ear plugs should be worn.

The bright light from the arc contains ultraviolet rays which are harmful to the eye. Arc welding goggles must be worn when looking directly at the arc.

2. Before Starting Torch

Make sure that all connections for gas, water and electricity are correctly made and secure. Make sure there is a constant supply of cooling water and working gas (dry nitrogen).

Figure 2. Plasma Torch Performance Data

Figure 3. Exit Gas Temperatures of the Plasma Torch

3. Starting the Plasma Torch

- a. Turn on the circulating water pump.
- b. Turn on the power supply main switch, set current control to 25A.
- c. Turn on gas supply, adjust N_2 flow through the torch to 120 on rotameter.
- d. After making sure the gas and water are flowing, turn on the arc starting switch. The torch should start after a 2-second delay. The switch should be left on.

4. Running the Plasma Torch

- a. Adjust the N_2 flow to desired value (not below 80 on rotameter).
- b. Adjust the arc current to desired value (not over 50A).
- c. Record arc voltage, current, gas flow, check from time to time.

5. Terminating the Plasma Torch

- a. Turn off the starting switch. The arc should stop.
- b. Turn off gas flow and power supply main switch. Keep the cooling water on until the furnace is cooled down sufficiently.

6. Check Points During Operation

- a. Cooling water circulating normally both in the torch body and in the cathode. No water leak at any point.
- b. Gas flow steady at set rate.
- c. Arc voltage steady at calibrated value. When new electrodes are installed, adjustment in the axial position of the cathode may be necessary to reproduce the arc voltage value at given arc current and gas flow.
- d. If any abnormality occurs, stop the plasma torch and examine the torch, the gas, water and electrical circuits.

7. Maintenance

After about 50 hours of running time or when operation shows irregularity, examine the electrodes for erosion. If there is excessive erosion, the parts should be replaced by new ones.

Appendix References

1. Huffman, G.P., et al., Fuel, 68, p.485 (1989).
2. Haussmann, G.J. and Kruger, C.H., 22nd Symp. (Int.) on Combustion, the Combustion Institute, p.223 (1988).
3. Kobayashi, H., et al., 16th Symp. (Int.) on Combustion, the Combustion Institute, p.411 (1977).
4. Field, M.A., Combustion and Flame, 13, p.237 (1969).
5. Saito, M., et al., Combustion and Flame, 87, p.1 (1991).
6. Hamling, P., "1700°C Rapid Cycle Furnace Insulation Design", Publication of Zircar Products, Inc., Florida, NY (1987).

PROJECT MANAGEMENT REPORT

March 1, 1992 through May 31, 1992

Project Title: Cooperative Research on the Combustion Characteristics of Cofired
Desulfurized Illinois Coal and Char with Natural Gas

Principal
Investigator: Richard O. Buckius, UIUC

Other
Investigators: Cheng-Kang Wu, Herman Krier, and James E. Peters, UIUC

Project Monitor: Dr. Kenneth K. Ho, CRSC

COMMENTS

The attached material indicates that this budget is very close to predictions.

SCHEDULE OF PROJECT MILESTONES

Project Title: Cooperative Research on the Combustion Characteristics of Cofired Desulfurized Illinois Coal and Char with Natural Gas

Principal Investigator: Richard O. Buckius, UIUC

Other Investigators: Cheng-Kang Wu, Herman Krier, and James E. Peters, UIUC

Project Monitor: Dr. Kenneth K. Ho, CRSC

Milestones:

- A. DTFF aggregate flotation parent and treated coal parent ash data
- B. DTFF aggregate flotation and treated coal ash data
- C. Technical Reports
- D. Project Management Reports

Comments:

The ash data analysis that was provided by an external laboratory yielded some contradictory results and must be reevaluated. This is the reason for the extension of the item A. milestone.

END

**DATE
FILMED**

12 / 7 / 92