Real Time Flame Monitoring of Gasifier Burner and Injectors

FINAL REPORT

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**Serguei Zelepouga
Alexei Saveliev**

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**Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, IL 60018**

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Abstract

This Final report is submitted to the United States Department of Energy in partial fulfillment of the contractual requirements for the project titled, “Real Time Flame Monitoring of Gasifier Burner and Injectors”, under co-operative agreement number **DE-FS26-02NT41585**. This project is a multistage effort with the final goal to develop a practical and reliable non-intrusive gasifier injector monitor to assess burner wear and need for replacement. The project team included the National Energy Technology Laboratory (NETL), Gas Technology Institute (GTI), North Carolina State University, and ConocoPhillips. This report presents the results of the sensor development and testing initially at GTI combustion laboratory with natural gas flames, then at the Canada Energy Technology Center (CANMET), Canada in the atmospheric coal combustor as well as in the pilot scale pressurized entrained flow gasifier, and finally the sensor’s capabilities were demonstrated at the Pratt and Whitney Rocketdyne (PWR) Gasifier and the Wabash River Repowering plant located in West Terre Haute, IN.

The initial tests demonstrated that GTI gasifier sensor technology was capable of detecting shape and rich/lean properties of natural gas air/oxygen enriched air flames.

The following testing at the CANMET’s Vertical Combustor Research Facility (VCRF) was a logical transition step from the atmospheric natural gas flames to pressurized coal gasification environment. The results of testing with atmospheric coal flames showed that light emitted by excited OH* and CH* radicals in coal/air flames can be detected and quantified. The maximum emission intensities of OH*, CH*, and black body (char combustion) occur at different axial positions along the flame length. Therefore, the excitation rates of CH* and OH* are distinct at different stages of coal combustion and can be utilized to identify and characterize processes which occur during coal combustion such as devolatilization, char heating and burning.

To accomplish the goals set for Tasks 4 and 5, GTI utilized the CANMET Pressurized Entrained Flow Gasifier (PEFG). The testing parameters of the PEFG were selected to simulate optimum gasifier operation as well as gasifier conditions normally resulting from improper operation or failed gasifier injectors. The sensor developed under previous tasks was used to assess the spectroscopic characteristics of the gasifier flame. The obtained spectral data were successfully translated into flame temperature measurements. It was also demonstrated that the

reduced spectral data could be very well correlated with very important gasification process parameters such as the air/fuel and water/fuel ratio. Any of these parameters (temperature, air/fuel, and water/fuel) is sufficient to assess burner wear; however, the tested sensor was capable of monitoring all three of them plus the flame shape as functions of burner wear. This will likely be a very powerful tool which should enable significant improvements in gasifier efficiency, reliability, and availability.

The sensor technology was presented to the project's industrial partner (ConocoPhillips). The partner expressed its strong interest in continuing to participate in the field validation phase of GTI's Flame Monitor Project. Finally the sensor was tested in the PWR (Pratt & Whitney Rocketdyne) gasification plant located at GTI's research campus and at the ConocoPhillips industrial scale gasifier at Wabash River Indiana. The field trials of the GTI Gasifier sensor modified to withstand high temperature and pressure corrosive atmosphere of the industrial entrain flow gasifier. The project team successfully demonstrated the Gasifier Sensor system ability to monitor gasifier interior temperature maintaining unobstructed optical access for in excess of six week without any maintenance. The sensor examination upon completion of the trial revealed that the system did not sustain any damage and required minor cleanup of the optics.

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Introduction

Technologists have long understood the rich potential of optical flame sensors to maintain burners or coal gasifier injectors at optimum performance, to decrease emissions of CO and NO_x, to determine burner or injector wear, and to precisely turn down and adjust firing rates. Sensors monitoring broad infrared (IR), visible, and ultraviolet (UV) radiation are routinely used today to monitor flames. UV and IR sensors are built into flame safety and control devices.

Conventional analog and digital cameras are used to monitor flame shape and length. These sensors allow furnace operators to manually adjust appropriate burner or coal injector controls to change flame length or firing rate as well as to maintain safe and stable combustion. The sensitivity and design of these sensors make them incapable of deeper qualitative and quantitative monitoring and analysis of complex combustion processes such as coal gasification.

The optical flame sensor currently developed at GTI is expected to extend the capabilities of existing combustion sensors. This sensor not only registers the presence of UV or IR light, but also monitors flame properties and flame position relative to the injector by collecting spatially resolved spectroscopic images of the flame radiation. The high temperatures and the chemically-active environment present in flames produce a number of excited species. Emission signatures of these species can be an effective tool for real-time active control systems and diagnostic sensors.

UV and IR emission spectroscopy have been recognized as valuable tools for non-intrusive flame temperature, structure, and species analysis. To date, significant progress has been made in understanding the spectroscopic features of gaseous hydrocarbon flames and methane flames in particular. Less attention has been paid to spectroscopic studies of coal combustion and gasification.

Objectives

The project objective is to develop a reliable, practical, and cost-effective means to monitor coal gasifier burner and injector flame characteristics and accurately predict burner wear and need for replacement. The operation of a fuel-rich flame in a gasifier environment requires precise control of gasifier parameters to ensure flame stability and high gasification efficiency. Precise control of the gasifier flows is needed to maintain the flame at rich conditions yet not allow low enough temperatures that would lead to reduced slug viscosity and solidification. Alternatively, operating too close to stoichiometry may result in prohibitively high temperatures and subsequent wear of the burner and refractory.

Scope of Work and Deliverables

This project includes modification of a developmental stage GTI optical flame sensor to serve as a flame characteristics sensor for burners and injectors on coal gasifiers. This R&D effort is divided into seven tasks. In Task 1, a developmental GTI flame characteristic sensor was modified to monitor selected UV, visible, and/or near-IR wavelengths to characterize fuel mixing, flame shape, and flame fuel rich and fuel lean zones. The deliverable of Task 1 was a topical report describing the modified flame sensor.

In Task 2, the flame sensor was tested with specially designed and built laboratory gas-air-oxygen burners. The burners were operated over a wide range of firing conditions from fuel rich to fuel lean and over a range of deteriorating burner conditions. The deliverables of Task 2 were a lab-scale test plan and a topical report containing the results of the flame sensor tests including data analysis and conclusions.

Task 3 was added at a later date to the overall scope of the project after the completion of Tasks 1 and 2. A justification for adding Task 3 to the project is presented in the section “Work Effort under Task 3” presented later in this report. In Task 3 the sensor was modified for testing at the Vertical Combustor Research Facility (VCRF) at the CANMET Energy Technology Center (CETC). The results of the tests were used to further define the desired test parameters for further testing. Spectrally resolved and video images were collected from stable and unstable flames near “blow off” conditions. The obtained data were analyzed in order to establish the correlation between flame spectral characteristics as well as spatial intensity distribution and

flame stability. The deliverables of Task 3 were a bench-scale test plan and a topical report containing the results of the flame sensor tests including data analysis and conclusions.

In Tasks 4 and 5 the sensor was tested at the CETC pressurized entrained flow gasifier (PEFG). Efforts were focused on obtaining accurate and repeatable flame characteristics including flame shape, mixing, and fuel rich and lean areas of the flame. The sensor hardware was simplified to make it more practical, in preparation for testing on an industrial gasifier. Other components needed for industrial tests were specified, including a view port of cooled periscope, wiring, etc. The deliverables of Task 4 were a bench-scale optimum burner condition test plan, a topical report containing the results of the flame sensor tests including data analysis and conclusions, and a description of all modifications made to the flame sensor including design drawings.

During Task 6 the Gasifier sensor was tested on a pilot-scale Pratt & Whitney Rocketdyne (PWR) Gasifier. The objective of this effort was demonstration of the sensor capabilities to monitor flame temperature. Also the spectroscopic data were analyzed to determine the specific flame characteristics that can be correlated with burner deterioration and process inefficiency. The deliverable of Task 6 is a report containing the results of the flame sensor tests including data analysis and conclusions, as well as a description of the experimental setup and all modifications.

In Task 7 the flame sensor was further modified in preparation for testing on a working industrial coal gasifier. Modifications included making the sensor and computer interface more rugged for industrial operation, selecting appropriate probes, housings, and supports for the sensor in order to have optical access through the burner or the wall, simplifying hardware and connections so the complete sensor package can be transported and installed on site; and designing any needed cooling, optical, or electrical protection. Further, plans were made to modify, if needed, access points to the combustion chamber or the burner/injector at specific locations.

In Task 8 of the sensor development the sensor was installed and tested on the Wabash River industrial gasifier in West Terre Haute, IN. The test was intended to acquire coal gasifier burner operation data collected in the beginning, middle and late stages of the life of the burner. The goal of this task was to determine the fundamental relationship between burner wear and flame characteristics in a working industrial gasifier. The deliverables of Task 8 are a gasifier

flame sensor test plan and a report containing the results of the flame sensor tests including data analysis and conclusions.

The stages and timeline of the project are summarized in Table 1 below.

Table 1 Project stages and timeline

Stage	Task	Period of performance	Location
Laboratory development	Flame Characterization Sensor Modification	December 2002 – February 2003	GTI, Des Plaines IL
	Lab-Scale Sensor Testing	March 2003 – December 2003	
Pilot Scale Testing	Sensor Testing at Vertical Combustor	January 2004 – July 2005	CANMET, Ottawa, Canada
	Sensor Testing at CANMET Gasifier, Optimum Burner Condition	July 2005 – July 2006	
	Sensor Testing at CANMET Gasifier. Variable Burner Condition	August 2006 – February 2007	
	Testing at Pratt and Whitney Rocketdyne (PWR) Gasifier	January 2010 – April 2011	
Field Demonstration	Preparation for Testing at Wabash Plant	April 2007 – September 2010	GTI, Des Plaines IL West Terre Haute, IN.
	Field Testing in Wabash River Gasifier	October 2010 – August 2011	West Terre Haute, IN

Discussion

Laboratory development and testing

During Tasks 1 and 2 of the project two laboratory-scale versions of spectroscopic sensors were developed and tested in the GTI combustion laboratory. Both versions utilized similar sensing approaches and hardware configurations. In both units, flame radiation was first

collected with a UV lens and is then processed spectroscopically and projected on a CCD (charged couple device) of a spectroscopic camera. The camera output was digitized and analyzed using data acquisition software and hardware. The first version of the laboratory sensor used an imaging spectrograph's grating to disperse the light and obtain light intensity distribution as a function of the wave length. This sensor configuration allowed acquiring high definition continuous flame spectra in one dimension. In order to scan an entire flame with the 1-D sensor multiple measurements were required. The 1-D sensor version was necessary while the sensor algorithm was still under development and spectral information had to be analyzed in its entirety. The second configuration used a filter wheel and a set of narrow band filters. This sensor was capable of acquiring two dimensional flame images at selected light wave bands. The disadvantage of this method was limited spectroscopic resolution and range. This sensor was applied only when the sensor algorithm had been developed and the number as well as width of the spectral bands of interest had been established. The photographs of the both sensor configurations are shown in Figure 1 and Figure 2.

Figure 1. Spectroscopic Optical Sensor.

Figure 2. 2-D Optical Sensor.

Both sensing approaches were tested with a specially designed flex-flame burner in the GTI Combustion Laboratory. The burner is capable of generating flames of variable size and flame properties. The sensors were capable of detecting shape and rich/lean properties of natural gas air/oxygen enriched air flames. Samples of the results obtained are shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8.

Figure 3. Photo of NG/Air flame

Figure 4. Photo of NG/Oxygen enriched Air flame.

Figure 5. OH image captured with 2-D sensor in NG/Air flame.

Figure 6. OH image captured with 2-D NG/Oxygen enriched Air flame.

Figure 7. OH profiles measured in NG/Air flame with 1-D sensor.

Figure 8. OH profiles measured in NG/Oxygen enriched Air flame with 1-D sensor.

Testing at Vertical Combustor Research Facility (VCRF)

Experimental Setup and Sensor Modifications

The 1-D sensor was utilized in pilot scale testing on the VCRF because of the need for highly resolved continuous spectra. The same configuration was used in subsequent tests on Pressurized Entrained Flow Gasifier (PEFG). A new optical interface was developed. The interface allows images to be acquired through an observation port as small as 2" in diameter and transfers flame light data at a distance of 30 feet using an optical fiber bundle. Figure 9 is a schematic of the GTI gasifier sensor installed on the Vertical Combustor. The light-collection assembly is attached to the optical access port with a specially-designed adapter. The assembly consists of a beam splitter, a 105 mm UV lens, a fiber-optic adapter, and a fiber-optic bundle. The beam splitter divides the collected flame image into two images of the same geometry but lower intensity. The first image is transferred to an imaging spectrograph through a 30-foot fiber optical bundle. The image is spectrally dispersed, recorded, and analyzed. The second image is collected by a digital video camera and is recorded concurrently on a tape and on the hard drive of the data acquisition computer.

The sensor collects a narrow strip of light (light emission profile) and spectrally disperses it on a 256 x 1024 spectroscopic charge-coupled detector (CCD). Therefore, the sensor data acquisition system can produce a two-dimensional array containing spectral information on one axis (intensity per wavelength) and spatial information on the other. Equipped with a 10-fiber fiber bundle the sensor is capable of acquiring and displaying 10 spectra from various flame locations instantaneously.

Figure 9. Multipoint Spectrally Resolved Imaging of the Coal Flame.

The geometry and sizing of the optical access hardware is shown in Figure 10. The spectral characteristics of the flame are measured along the flame length using an array of ten optical fibers assembled into an optical fiber bundle as it shown in Figure 10. Optical access dimensions and geometry. . The area viewed and analyzed with the GTI sensor is shown in red. The current optical setup is designed for relatively small (on the order of 12") flames generated in the CANMET Pressurized Gasifier and Vertical Combustor. Nevertheless, with some modification to the fiber bundle structure this approach can be adapted for flames of any size.

Figure 10. Optical access dimensions and geometry.

Figure 11. GTI Gasifier Sensor Mounted on Vertical Combustor at CANMET.

Selection of Test Points on the VCRF

The experiments on the VCRF were designed to test the flame sensor in order to determine the changes in flame characteristics that occur as gasifier burners and injectors

deteriorate with long-term use. The rationale behind each test and how it relates to injector wear is shown in the list below, whereas the detailed results are given in the following sections.

1. Transition from Natural Gas to Coal: Natural gas is used to preheat the combustor chamber. The transition tests were conducted to establish the difference in spectral characteristics between coal and natural gas flames.
2. Coal Feeding Rate Variation: The situation in which the injector is damaged and fuel and oxygen are not mixing and burning at optimum conditions was simulated by changing the oxygen to coal ratio.
3. Coal Injection Velocity: When the injector overheats and warps the fuel injection orifice is likely to reduce in diameter. This will lead to an increased fuel jet velocity. This condition was simulated by increasing the fuel injection velocity.
4. Swirl Variation: The secondary air injection angle is intended to enhance the mixing of the secondary combustion air to the primary coal/air stream. Unfortunately, the PEFG currently has no provision for varying the secondary air injection angle. However, these tests on the VCRF were deemed necessary since the majority of industrial gasifiers, including the gasifier operated by ConocoPhillips, do use secondary air injection.

Experimental Results

The Vertical Combustor was initially preheated with a natural gas flame for approximately 24 hours. The natural gas fuel was gradually replaced with pulverized coal while keeping the overall fuel mass the same. The flame images in Figure 12, Figure 13, Figure 14, and Figure 15 show the flame visible envelope during transition from NG to coal. The images were obtained by a water cooled camera inserted deep inside the combustor. The radiation emitted by the natural gas flame (see Figure 12) cannot be detected with conventional video cameras. The strong background radiation emitted by the hot refractory overwhelms the flame radiation. When coal is added visible flame radiation increases dramatically. Natural gas visible flame light is a combination of radiations emitted by the hot products (water and carbon dioxide), excited radicals and soot. The visible light emitted by the coal flames also contains radiation from burning coal particles. Hot solid carbon particulates are much better emitters, therefore the coal/natural gas and coal flames are much more luminous than natural gas flames.

Figure 12. 20 kg/hr NG.

Figure 13. 10 kg/hr NG, 10 kg/hr Coal.

Figure 14. 5 kg/hr NG, 15 kg/hr Coal.

Figure 15. 0 kg/hr NG, 20 kg/hr Coal.

To quantify the OH and CH radiation intensities, the OH and CH intensity peaks were integrated and plotted for each tested flame condition (see Figure 16, Figure 17). Figure 16 and Figure 17 show that increasing the coal fraction in the natural gas/coal fuel mixture results in a decrease of OH radical emission and an increase of CH radiation intensity while the background intensity rises with the coal feed increase. The ration of CH/OH emission intensities (Figure 18) can be used to access natural gas to coal ration in natural gas/coal hybrid flames.

Figure 16. CH Intensity.

Figure 17. OH Intensity.

Figure 18. CH/OH Ratio.

Figure 19. Light Intensity at 410 nm.

Coal feeding rate variation

In this test, coal injection feed (kg/hr) was incrementally decreased from 20 kg/hr to 10 kg/hr while maintaining the same oxidant level; in this case, atmospheric air. In effect, the coal flame became leaner with each point. Below 10 kg/hr coal feed the flame became too unstable and extinguished. As Figure 20, Figure 21, Figure 22 show, the flame temperature and visible flame light emission decreased with decreasing coal feed. This visual result is verified by the radical species intensity peaks shown in Figure 23, Figure 24, Figure 25, and Figure 26. It is worth noticing that the ratio of CH to OH intensity remained relatively unchanged for fibers 1 and 5. The intensity ratio for fiber number 9 decreased, possibly the result of a shorter flame length.

Figure 20. 20 kg/hr coal.

Figure 21. 15 kg/hr coal.

Figure 22. 10 kg/hr coal.

Figure 23. CH Intensity.

Figure 24. OH Intensity.

Figure 25. CH/OH Ratio.

Figure 26. Light Intensity at 410 nm.

Coal injection velocity

The effect of changing the coal injection velocity was examined during this test. The burner utilized in the vertical combustor introduces pulverized coal mixed with air (primary air) into the combustor. An annular pipe surrounding the primary air/pulverized coal mixture tube introduces secondary air into the combustor to complete the combustion of the coal/air mixture. The coal injection velocity was varied by increasing the delivery pressure of the secondary air stream. As Figure 27, Figure 28, Figure 29, Figure 30 show, increases the coal injection velocity results in the flame being pushed away from the burner mouth creating an unstable flame front at levels 2 and 3. The spectral results shown in Figure 31, Figure 32, Figure 33 indicate that the flame intensity of OH and CH decrease with increasing coal injection velocity. This result can be explained as follows: as the secondary air pressure is increased, the overall air/pulverized mixture is allowed less time to mix and combust fully. In this mode of operation, unburned coal particles are expected to exit the combustor chamber.

Figure 27. Base Velocity.

Figure 28. Increased Velocity Level 1.

Figure 29. Increased Velocity Level 2.

Figure 30. Increased Velocity Level 3.

Figure 31. CH Intensity.

Figure 32. OH Intensity.

Figure 33. CH/OH Ratio.

Figure 34. Light Intensity at 410 nm.

Swirl variation

This test examined the impact of varying the swirl number of the combustion air on the structure of the pulverized coal/air flame. The swirl number quantifies the rotational momentum of the secondary air with respect to the axial momentum of the gases passing through the burner. The swirl index is an arbitrary unit corresponding to the injection angle setting of the swirl vanes on the burner. This injection angle is intended to enhance the mixing of the secondary combustion air with the primary coal/air stream. An increase of the swirl index results in the increase of the swirl number. The mixing of the secondary air stream with the primary coal/air stream starts inside the burner mouth and continues in the combustion chamber. As Figure 35, Figure 36, Figure 37, and Figure 38 show, increasing the swirl number promotes more rapid

mixing of the coal and the oxidant which results in more intense combustion closer to the burner mouth.

Therefore, the flame front moves closer to the burner mouth and even enters the burner mouth at maximum swirl (what swirl number produced this result?). Both the OH and CH peak intensities increase as the swirl index increases (Figure 39 and Figure 40). This is expected since the increased coal/oxidant mixing promotes complete and intense combustion resulting in light emission from excited molecules and radicals.

Figure 35. Swirl 6.

Figure 36. Swirl 7.

Figure 37. Swirl 10.

Figure 38. Swirl 12.

Figure 39. CH Intensity.

Figure 40. OH Intensity.

Figure 41. CH/OH Ratio.

Figure 42. Light Intensity at 410 nm.

Conclusions

The results proved that light emitted by excited OH^* and CH^* radicals in coal/air flames can be detected and quantified. The information in Figure 39, Figure 40, Figure 41, and Figure 42 shows that the maximum emission intensities of OH^* , CH^* , and black body (char combustion) occur at different axial positions along the flame length. An illustration of this idea is shown in Figure 43. Therefore, the rates of exited CH^* and OH^* are distinct at different stages of coal combustion. It is reasonable to believe that the characteristic stages, or zones, where devolatilization, char heating and burning occur can be identified and possibly quantified by correlating the CH^* and OH^* intensity information at given flame zones.

Figure 43. OH and CH intensity distributions.

The GTI gasifier sensor is capable of detecting the effects on coal flames caused by swirl variation, injection velocity variation and oxidizer to coal ratio.

Testing at CANMET Pressurized Entrained Flow Gasifier

Figure 44 shows the experimental setup utilized in the sensor testing at CANMET Pressurized Entrained Flow Gasifier (PEFG). The sensor was not modified from the configuration used during the VCRF test under Task 3. The sensor's light-collection assembly (LCA) already described in the previous sections was mounted in the upper section of the gasifier. The assembly was flanged to the gasifier 2" optical access port. The port was purged with nitrogen to prevent deposition of coal particles on the port quartz window. The gasifier reactor was located in the high-pressure safety section of the gasification facilities. Therefore flexible 30 foot long fiber optical and video transfer cables were used to connect the LCA and the sensor, which was kept in the control room next door to the gasifier.

Figure 44. Sensor Setup at Pressurized Entrained Flow Gasifier.

The CANMET entrained flow gasification pilot plant (Figure 45) was initially designed to use dry coal feed. It consists of a coal hopper from which dry coal is injected into the vertical refractory-lined reactor. The streams of air and oxygen are supplied from the gasifier top establishing a rich coal flame. The propane/natural gas supply serves for the initial preheating of the reactor. The coal gasification occurs as coal particles are conveyed downstream through the

reactor volume. The hot gaseous products exit at the bottom of the reactor where they are separated from the solids and quenched by the water. The coal feed rate typically varies from 5 to 20 kg/hour. The gasifier renovation program currently underway at CANMET includes the upgrade of the existing gasification system for operation at 1.5 MPa pressure and temperatures as high as 1800 °C. Additionally, modifications allowing dry coal feed and coal-water slurry feed were incorporated into the fuel supply system. .

Figure 45. CANMET entrained flow gasifier.

Testing approach

The following injector malfunctions were simulated during the tests:

- Injector damage leading to improper fuel and oxidant mixing. This situation was simulated by changing the oxygen to coal mass ratio (oxygen/coal ~ 0.8-0.95). Injector damage leading to incorrect amount of steam or slurry moisture being fed into the gasifier. The amount of steam injected into the gasifier was varied (steam/coal ~ 0.2- 0.3) to simulate this type of injector damage.
- Flame temperature deviation from optimum. Temperature was varied by changing the oxygen to fuel ratio.

Table 2. Test Matrix.

P, kPa	C, kg/hr	O₂, kg/hr	H₂O, kg/hr	O₂/Coal	H₂O/Coal
30	10	8.5	2.0	0.85	0.20
30	14	11.9	2.8	0.85	0.20
30	14	11.9	4.2	0.85	0.30
30	14	13.9	4.2	0.99	0.30
30	14	13.9	2.8	0.99	0.20
750	10	8.5	2.0	0.85	0.20
750	10	9.0	2.0	0.90	0.20
750	10	9.5	2.0	0.95	0.20
750	10	9.0	2.5	0.90	0.25
750	10	9.0	3.0	0.90	0.30
750	14	11.9	2.8	0.85	0.20
750	14	11.9	2.1	0.85	0.15
750	10	8.5	2.0	0.85	0.20
750	10	9.0	2.0	0.90	0.20
750	10	9.5	2.0	0.95	0.20
750	10	9.0	2.5	0.90	0.25
750	10	9.0	3.0	0.90	0.30
750	14	11.9	2.8	0.85	0.20
750	14	11.9	2.1	0.85	0.15
750	14	11.9	1.4	0.85	0.10

Experimental procedure

The CANMET gasifier can be run continuously for approximately 6-8 hours. Therefore each new day of the testing was started with the unit preheating and establishing baseline conditions. The conversion to coal operation was initiated after reaching the required preheating temperature. The coal gasification tests were performed with near atmospheric and 750 kPa pressures. The gasifier operation was controlled by the feed rates of coal, oxygen, and steam. The feed rates and corresponding oxygen-to-coal and steam-to-coal ratios are listed in Table 2. The spectral data collected for each gasification condition contain information on the following features: blackbody profile (BB), sodium lines (Na), CH radical (CH), OH radical (OH), and potassium line (K).

The following experimental settings were used for data collection:

- Blackbody – grating 150 grooves/mm, central position 450 nm, exposure 0.2s
- Na – grating 1200 grooves/mm, central position 585 nm, exposure 1.0s
- CH – grating 1200 grooves/mm, central position 430 nm, exposure 10s
- OH – grating 1200 grooves/mm, central position 310 nm, exposure 300s
- K – grating 1200 grooves/mm, central position 410 nm, exposure 100s

The spectrometer slit was set to 500 microns for all the experiments conducted. Two types of diffraction gratings were utilized for flame light dispersion. The high resolution holographic grating (1200 grooves/mm) was used to obtain highly resolved spectral features of the exited radicals while the coarser grating (150 grooves/mm) was needed to capture the wide-band black body spectra.

Analysis and Interpretation of Spectral Data

The key flame spectral features are shown in Figure 46. These features are clearly visible and span a range from 275 to 625 nm. The emission band of OH* radicals is positioned at ~ 310 nm. The CH* radical band is close to 430 nm. Two linear spectra of potassium and sodium are observed at 410 nm and 590 nm respectively. The blackbody radiation produces a strong background spectrum with its intensity rapidly rising with increasing wave length. The blackbody radiation in the natural gas flame is not emitted by the flame but rather the hot reactor refractory. On the other hand, in coal gasification, the main source of the blackbody radiation is the heated coal particulates. Therefore the blackbody radiation approach can be employed primarily for determining temperatures in coal flames. The blackbody spectra of the natural gas flame and two coal flames with O₂/C ratios of 0.9 and 0.95 are shown in Figure 47. The blackboard curves representing the coal flames exhibit much steeper slopes. These indicate that the temperature of burning coal particles are significantly higher than the temperatures of the reactor walls.

Figure 46 Key diagnostic features of the flame

Figure 47 Intensity of Blackbody Radiation for Natural Gas and Coal Flames

The following procedure was used to evaluate temperatures of the coal flame. The blackbody radiation emitted by the refractory walls was used as a calibration source with known blackbody

temperature – 1350 K. The spectral sensitivity of the window/sensor/fiber/spectrometer/CCD assembly was found as:

$$R(\lambda) = \text{Refractory Signal } (\lambda) / E(\lambda, T_{ref})$$

where $E(\lambda, T)$ is the spectral intensity of the blackbody for corresponding refractory wall temperature. The spectral intensity of blackbody radiation $F(\lambda)$ from the flame was found as:

$$F(\lambda) = R(\lambda) * E(\lambda, T_F)$$

where $E(\lambda, T)$ is the spectral intensity of the blackbody defined by Planck's law. The best fit for the $F(\lambda)$ distribution is used to determine the temperature profile of the coal flame. The emissivity of the radiating bodies within the coal flame is assumed to be 1. The obtained average flame temperatures are equal to 1610 K and 1740 K for the tested O_2/C ratios of 0.9 and 0.95, respectively. The accuracy of the absolute measurements was conservatively estimated at 50 K. The spectral features of CH^* radicals are strong in the natural gas flame due to the presence of the hydrocarbon bond. Concurrently CH^* emissions in the coal flames are almost indistinguishable due to the relatively low hydrogen content and the strong background blackbody radiation (Figure 48). Therefore the CH^* emission peak was not used in the further analysis of the test results. The analysis of the spectral data for various firing conditions reveals that OH^* intensities are a strong indicator of the oxygen/coal and steam coal ratios. These results are presented in Figure 49 for two H_2O/C ratios of 0.2 and 0.3. It can be clearly observed that OH^* intensity was higher for H_2O/C ratios of 0.2 suggesting that water present in the reaction zone reduces the OH^* emission. Furthermore OH^* intensity increased with increase in oxygen content if steam load was kept constant. The OH^* signal increased from 60 a.u. to 140 a.u. with increase of O_2/C ratio from 0.85 to 1 for $H_2O/C=0.3$. At the same time for $H_2O/C=0.2$, the OH^* signal increased from 200 a.u. to 660 a.u. in the same interval of O_2/C ratios. This suggests the OH^* intensity can serve as a good indicator for variations of oxygen and steam contents. These data also agree well with the existing kinetic models of the OH^* excitation in hydrocarbon flames.

Figure 48. CH* spectra in natural gas (left) and coal (right) flames.

Figure 49. Variation of OH* intensity with oxygen/coal and steam/coal ratios.

The concentration of OH* typically increases with oxygen enrichment while steam addition leads to an increase of the non-radiative quenching of excited OH* in collision with water

molecules. The sodium lines positioned at ~ 590 nm represent an excellent diagnostic feature due to the high relative intensity and clear separation from the background (Figure 50). It can be clearly observed that the sodium doublet structure changes significantly with the transition from the natural gas flame to the coal flames as well the coal flame parameters variation. The sodium lines in the natural gas flame (Figure 50, left) are completely separated and the line at the lower wavelength is substantially higher. The peaks are partially overlapped in the coal flame cases. The separation pattern and the ratio of the line and the background intensities vary. All these features can be used for flame diagnostics. For example, the relative intensity of the sodium line (ratio of line intensity to the intensity of the background) depends strongly on the steam-to-coal ratio (Figure 51). The figure shows that the relative intensity of the sodium lines rapidly drop with the increase of the steam-to-coal ratio. When the steam-to-coal ratio is increased from 0.2 to 0.3 the relative intensity of the sodium lines decrease from ~ 5.4 to ~ 2 . This shows almost 3 times increase with the increase in H_2O/C of 50%.

Figure 50. Structure of sodium lines in natural gas preheating flame (left) and coal flames with $O_2/C=0.85$ and $H_2O/C=0.2$ (center) and $H_2O/C=0.3$ (right).

Figure 51. Variation of relative intensity of Na lines with steam-to-coal ratio for $O_2/C=0.85$.

Conclusions

The spectral features of coal flames (OH^* , CH^* , K, Na, Blackbody) are comparatively analyzed for their application to coal flame monitoring. It has been shown that strong blackbody background radiation generated by coal particulates can be effectively used for reconstruction of flame temperature with accuracy close to 50 K. The emission profiles of OH^* radicals showed a strong dependence on the oxygen-to-coal and steam-to-coal ratios. Particularly, the OH^* intensity rapidly increases with reduction of the steam-to-coal ratio. The OH^* intensity also increases with oxygen enrichment. The CH^* emissions, which are typically strong in hydrocarbon flames, are below the noise level in the recorded coal spectra. Sodium duplet lines represent excellent features for coal flame diagnostics due to their high relative intensity and strong variation in spectral structure as functions of flame parameters.

Testing at PWR gasifier

Figure 52 shows a schematic of the sensor installation in the PWR gasifier. The GTI sensor utilized the existing gasifier optical light collection system (Optical Head). A beam splitter was added to allow access to the flame without interfering with operation of the flame detector currently used for the PWR gasifier flame monitoring.

Figure 52. Schematic of Sensor Installation in PWR Gasifier.

The beam splitter allowed a portion of the flame light collected by the Optical Head to be transmitted through a fiber optical cable to the imaging spectrograph where the light was spectrally dispersed, recorded, and analyzed. The obtained spectra are expected to allow assessment of flame temperature, oxidizer to fuel ratio, and other flame properties.

Experimental Setup

Prior to the installation of the gasifier sensor on the PWR gasifier the project team conducted calibration tests to establish the combined spectral sensitivity of the new injector

window, beamsplitter, and fiber-optic bundle. Figure 53 and Figure 54 show a schematic and photograph of sensor calibration setup. The PWR injector was placed between the black body radiation source and the light collecting optics (beam splitter).

Figure 53. Schematic of the sensor calibration setup.

Calibration spectra were collected in the 400 -700 nm spectral range using 300 and 1200 grooves- per-millimeter gratings. The calibration spectra were utilized to determine and compensate for the flame spectrum distortions caused by the flame light attenuations in the injector window, beamsplitter, and the fiber optical bundle.

Figure 54. Photograph of the sensor calibration setup.

The Gasifier sensor was installed in the P&W Rocketdyne gasifier facilities as shown in Figure 55. The lens normally utilized to collect radiation for the gasifier flame detection system was replaced with the beam splitter. The new optics allowed simultaneous operations of the GTI Gasifier sensor and the flame detection system using a single optical access port.

Figure 55. Photograph of the new light collecting and splitting hardware installed on the PWR gasifier.

The spectroscopic equipment and data acquisition system (see Figure 56) were set up in a non-process side of the PWR gasifier bay and connected to the light collecting optics with a thirty-foot-long fiber-optic bundle.

Figure 56. Photograph of the Gasifiers sensor's spectroscopic and data acquisition setup.

The project team conducted spectroscopic sampling of the PWR flame during approximately two-week long testing that GTI and PWR conducted in March 2011. The variable parameters of the gasifier operation included: fuel feed, oxygen, and steam flow rates, oxygen to fuel ratio, gasifier pressure and fuel feed type.

Acquisition of Spectral Data at PWR Facilities

Seventeen (17) experimental conditions tested at PWR facilities and are numbered according to the test log as 110-118, 121-126, 130, and 131. These are summarized in Table 1. The spectrometer settings utilized during the spectrum acquisition are listed in Table 2. The data collected for each gasification condition contained the following spectral features: blackbody profile (BB), Sodium lines (Na), CH radical (CH), Potassium lines (K), Calcium lines (Ca), and Lithium line (Li).

The following experimental settings were used for data collection:

- Blackbody – grating 300 grooves/mm, central position 430 nm

- CH - grating 1200 grooves/mm, central position 430 nm
- Na, Ca – grating 300 grooves/mm, central position 590 nm
- Ca – grating 1200 grooves/mm, central position 565 nm
- Na – grating 1200 grooves/mm, central position 590 nm
- Li – grating 1200 grooves/mm, central position 600 nm

Table 3. Test parameters

Point #	Coal flow (lb/hr)	Oxygen Flow (lb/hr)	Steam Flow (lb/hr)	Gasifier pressure (psia)	Feed
110	800	620	75	400	Ill #6
111	1350	1250	150	400	Ill #6
112	1350	1374	150	400	Ill #6
113	1350	770	150	400	Ill #6
114	1620	1120	150	400	Ill #6
115	1350	1250	150	300	Ill #6
116	1350	770	150	400	Ill #6
117	1620	1120	150	400	Ill #6
118	1350	1250	150	400	Ill #6
121	1100	935	150	400	Ill #6
122	800	620	225	400	Ill #6
123	930	800	200	400	Joliet
124	930	100	200	400	Joliet
125	800	790	150	400	Joliet
126	930	915	200	300	Joliet
130	1350	1070	150	400	Sub-bit
131	1350	1070	150	400	Sub-bit

Table 4. Spectrometer settings.

Spectrometer Settings	1	2	3	4	5	6
Center (nm)	430	430	590	565	590	680
Grating (gr/mm)	300	1200	300	1200	1200	1200

Temperature Recognition using Blackbody Spectra

Temperature recognition was performed using a blackbody fit in a spectral range from 425 nm to 505 nm. The characteristic spectrum recorded using spectrometer setting #1 is shown in Figure 57. The gasification conditions correspond to the experimental point # 126.

The following procedure was used to evaluate the temperatures of the coal flame. A blackbody radiation emitted by a calibrated blackbody source with known temperature (1473 K) was recorded and stored as a calibration. The spectral sensitivity $R(\lambda)$ of the window/sensor/fiber/spectrometer/CCD assembly was found as:

$$R(\lambda) = C(\lambda) / E(\lambda, T_{ref})$$

where $C(\lambda)$ is the recorded spectrally-resolved calibration signal, and $E(\lambda, T_{ref})$ is the spectral intensity of the blackbody at known reference temperature. The spectral intensity $E(\lambda, T_{ref})$ is defined by the Planck's law.

The spectral intensity of blackbody radiation $E(\lambda, T_F)$ emitted from the flame can be found using the spectral sensitivity as:

$$E(\lambda, T_F) = F(\lambda) / R(\lambda)$$

where $F(\lambda, T)$ is the recorded spectrally-resolved flame signal. The best fit for the $E(\lambda, T_F)$ distribution is used to determine temperatures of the coal flame. The emissivity of radiating bodies in the coal flame is assumed to be 1. The obtained average flame temperatures are in the range from 1450 K to 1720 K for the experimental conditions tested (Figure 58). The accuracy of the measurements was estimated to be 100 K.

Figure 57. Spectral region selected for temperature measurements using the blackbody fit.

Figure 58. Flame temperatures obtained using the blackbody fit of the spectral data.

Spectral features observed in a wavelength range from 350 nm to 500 nm

The spectral features of CH* radicals are strong in natural gas and hydrocarbon flames due to a presence of hydrocarbon bonds. In coal flames CH* emissions are almost indistinguishable due to the relatively low hydrogen content of coal and strong background blackbody radiation within the flame. As expected, CH* emissions were not observed as distinct peaks in the recorded spectra.

The characteristic spectral features of the coal flames in the range from 350 nm to 500 nm are shown in Figure 59 and Figure 60. The low resolution spectra taken with the spectrometer Setting #1 exhibit a number of pronounced atomic lines and molecular bands (Figure 59). One of the atomic lines, a Ca line at 423 nm, is present in all recoded spectra. Another common atomic line, a K (Potassium?) line at 405 nm, is present only for a few experimental conditions. This line appears along with a molecular band extending from 360 nm to 400 nm. This molecular

band requires further identification. The runs with experimental conditions leading to the appearance of the K line and the molecular band are listed in Table 4.

Figure 59. Characteristic spectral features of the coal flame in a wavelength range from 450 nm to 500 nm: (a) representative spectrum with the Ca line at 423 nm, (b) representative spectrum with the Ca line at 423 nm, the K line at 405 nm and molecular band in 360-460 nm range.

Table 5. Experimental conditions showing a presence of the potassium line at 405 nm and the molecular band in 360-400 nm range.

#	Experimental Conditions														
	112	113	114	115	116	117	118	121	122	123	124	125	126	130	131
1		x	X	x	x	x	x	x	x						x

The high resolution spectra taken using the spectrometer Setting #2 show several atomic lines and molecular bands (Figure 60). As expected, the strong Ca line at 423 nm appears in all recorded spectra. Other atomic lines in a wavelength range from 425 to 445 nm are present only under certain experimental conditions. These conditions are listed in Table 5. Some of these atomic lines belong to K and Hg (Mercury). Other lines require further identification. As expected, there is a close match between the experimental conditions listed in **Table 5** and **Table 6**.

Figure 60. Characteristic spectral features of the coal flame in a wavelength range from 405 nm to 445 nm: (a) representative spectrum with the Ca line at 423 nm, (b) representative spectrum with the Ca line at 423 nm, and the additional atomic lines appearing in the interval from 425 nm to 440 nm.

Table 6. Experimental conditions showing a presence of the additional atomic lines in the wavelength interval from 425 nm to 440 nm.

#	Experimental Conditions														
	112	113	114	115	116	117	118	121	122	123	124	125	126	130	131
2	x	x	x	x	X	x	x	x	x						x

Spectral features observed in a wavelength range from 530 nm to 620 nm

The low resolution spectra in the wavelength range from 530 nm to 620 nm were recoded using Setting #3 (Figure 61). A CaOH molecular bands near 555 nm and sodium lines near 590 nm were observed on these spectra.

Figure 61. Characteristic spectral features of the coal flame in a wavelength range from 530 nm to 620 nm:
(a) representative spectrum with the CaOH band and the Na duplet.

The sodium duplet usually represent an excellent feature for the diagnostic of coal flames due to high relative intensity and clear separation from the background. The structure of sodium the duplet changes significantly with variation of coal flame parameters. The lines are partially overlapping in coal flames. Such features as the relative intensity of saturated and unsaturated lines and the ratio of the line intensities to the continuum radiation can be used for diagnostics of various flame parameters. For example, the ratio of Na line intensity to the intensity of the background strongly depends on steam-to-coal ratio. The fine structure of the Na duplet was recorded using experimental Setting #5 (Figure 62).

Figure 62. Highly-resolved spectral features of the coal flame near the Na duplet.

Spectral features observed in a wavelength range from 660 nm to 700 nm

The high resolution spectra in the wavelength range from 660 nm to 700 nm were recorded with the spectrometer Setting #5. This setting is at the red limit of the employed spectral system. The only feature observed in these spectra is a Li line at ~670 nm (Figure 63A). . This line is present only at certain experimental conditions.

Figure 63. Highly-resolved spectral features of the coal flame in the wavelength range from 660 nm to 680 nm: (a) representative spectrum showing the Li line, (b) representative spectrum showing a uniform background.

The Li lines similar to the spectrum shown in Figure 14 A were observed at the experimental conditions are listed in Table 5.

Table 7. Experimental conditions showing the Li line at 671 nm.

#	Experimental Conditions						
	110	111	123	124	125	130	131
6	x	x				x	

Conclusions

The spectral features of coal flames (atomic lines of K, Na, Li and blackbody radiation continuum) are comparatively analyzed for applicability to coal flame diagnostics. It is shown that strong blackbody background radiation generated by coal particles can be used for the reconstruction of average flame temperature. The accuracy of the method is affected by the uniformity of the studied flames that could result in the strong reabsorption of the radiation

emitted from the central zone of the flame. The Ca line at 423 nm, the Na duplet at 590 nm, and the CaOH band at 555 nm appear at all recorded conditions. The appearance of other atomic lines and molecular bands depends on the experimental settings. This variance can be attributed to the variation of coal content or to the different firing conditions.

Testing at Wabash River Gasifier

Figure 64 shows a schematic of the sensor installation at the Wabash River gasifier. The flame image collected by the fiber-optic probe (FOP) is transmitted through a 30-foot long fiber-optic bundle to a sensor station. The image splitter divides the collected flame image into two images of the identical view as the original one but half of the original intensity. The first image is transferred to the imaging spectrograph where the image is spectrally dispersed, recorded, and analyzed. The second image is collected by the digital video camera, then simultaneously displayed and recoded on the data acquisition computer. The sensor station can be positioned in the direct vicinity of the gasifier. The enclosure is designed to protect the sensor equipment from seasonal temperature variations and coal dust and should allow short-term operator access and maintenance. Long-term monitoring is possible by connecting remotely to the sensor station over an Ethernet line.

Figure 64. Schematic of Sensor Installation at Wabash River Gasifier

Figure 65 shows a schematic of the water cooled fiber-optic probe (WCFOP). The WCFOP consists of a water-cooled, nitrogen-purged enclosure and fiber-optic bundle encased in a protective 1/4" stainless steel sleeve with a sapphire window assembly welded at the front end of the sleeve. The bundle enclosure is expected to withstand temperatures and pressures exceeding 550 psig and 600 °F, respectively.

Figure 65 General schematic of the FOP

Sensor installation

The probe was repaired and reinstalled at the Wabash gasifier during spring maintenance outage. The probe's sheathing and installation procedure was modified to prevent damage to the probe which occurred during a previous installation. The old sheathing was replaced with a less-flexible but more rugged one. A larger-diameter conduit was installed to house the flexible portion of the fiber-optic probe. To avoid damaging the fiber the probe was pushed through the conduit rather than pulled. A steel wire attached to the probe at multiple locations was utilized to carefully guide the flexible portion of the probe during installation into the 15-foot long conduit (Figure 66 and Figure 67).

Figure 66. Flexible portion of the probe installation into the new conduit

After the flexible portion of the probe was inserted into the conduit and connected to the camera, the ability of the sensor to capture images was verified to insure that no damage occurred during the installation.

Figure 67. Rigid portion of the probe installation into the water cooled enclosure.

Sensor calibration and testing procedures

The sensor testing was commenced immediately after the spring outage completion. The objectives of the testing were to validate the probe's ability to maintain unobstructed optical

access to the gasifier interior as well as to assess the accuracy of the sensor's temperature recognition algorithm.

The sensor software was programmed to continuously capture and record images of the gasifier interior. The collected images were analyzed using calibration curves obtained via the calibration described below.

The calibration experimental setup shown in Figure 68 and Figure 69 include: a blackbody source and a CMOS color video camera.

Figure 68. Wabash Sensor Calibration Experimental Setup (Schematic)

Figure 69. Wabash Sensor Calibration Experimental Setup (Photograph)

Figure 70. Image of the black body at 1292F

Figure 71. Image of the black body at 1120 F

The acquired images (Figure 70 and Figure 71) were first digitized and then processed to infer ratios of Red/Blue and Green/Blue signals using software developed by the project team. The obtained calibration curve is shown in Figure 72. The relation between temperature and R/B function is given as:

$$R/B = 53 + 609 * T$$

The inverse function expresses T as a function of R/B ratio. This function serves as an input in the thermal imaging software. The calibration coefficients are stored in a special calibration file and can be used with any color ratio to convert a color image to a 2-D temperature distribution plot.

Figure 72. Experimental calibration line for Red/Blue ratio

Experimental results

Figure 73 and Figure 74 show examples of the gasifier temperatures acquired with the GTI Gasifier sensor presented in non-dimensional form.

Figure 73. Temperature recorded the optical gasifier probe over 24 hour period

Figure 74. Temperatures recorded by the optical gasifier probe during 15 days. (9 pm, June 14 – 28, 2011)

Optical access

Figure 75 is a photograph of the probe taken inside the gasifier reactor during a short maintenance outage in July 2011. The picture shows that six months of continuous probe operation did not result in any slag obstruction (slagging over) of the probe optical opening. The white item in the middle of the photo is a paper towel placed into the probe's opening to prevent dust from getting inside the probe during the gasifier maintenance work while the nitrogen purge was turned off.

Figure 75. Photograph of the probe taken inside the gasifier reactor.

Figure 76, Figure 77, and Figure 78 are images of the gasifier interior collected with the gasifier sensor after two days, three weeks and five weeks of the probe operating. The figures show that gradual reduction in the window transparency likely due to solid particulate accumulation on the window.

Figure 76. Image of gasifier interior after two days of probe operation

Figure 77. Image of gasifier interior after three weeks of probe operation

Figure 78. Image of gasifier interior after five weeks of probe operation.

Comparison of the window's conditions before the probe installation (Figure 79) and after the six week run (Figure 80) confirmed a slow but substantial black powder accumulation did occur over time on the front of the window assembly in spite of the fact that the probe was continuously purged with nitrogen during the entire six weeks of probe testing.

Figure 79. Sapphire window before installation

Figure 80. Sapphire Window after Six Weeks of Operation

Conclusions and recommendations

The pilot scale and field tests demonstrated that the developed spectroscopic gasifier sensor is an excellent tool for the gasification process monitoring. It was shown that the strong blackbody background radiation generated by coal particulates can be effectively used for reconstruction of flame temperature with accuracy close to 50 K. The emission profiles of OH* radicals showed a strong dependence on the oxygen-to-coal and steam-to-coal ratios. Particularly, the OH* intensity rapidly increases with reduction of the steam-to-coal ratio. The OH* intensity also increases with oxygen enrichment. The CH* emissions, which are typically strong in hydrocarbon flames, are below the noise level in the recorded coal spectra. Sodium doublet lines represent excellent features for coal flame diagnostics due to their high relative intensity and strong variation in spectral structure as functions of flame parameters. These diagnostics capabilities can enable the gasifier operators to detect injector malfunctions and process inefficiencies will allow better planning of the injector maintenance and as result will help to improve the gasification process efficiency, safely and availability. The field trials at Wabash Gasifier proved that the developed water cooled probe is capable of maintaining unobstructed optical access for in excess of six week without any maintenance. The sensor examination upon completion of the trial revealed no damage. The probe was ready for reinstallation after a five-minutes-long cleanup of the optics.

At this point the project team believes that the most likely mechanism transporting solid particulates to the probe window is an entrainment of the petroleum coke particulates by the highly turbulent and recirculating flow of the purging nitrogen downstream of the window (Figure 81).

Figure 81. Highly turbulent purging nitrogen flow (Current configuration).

The entrainment problem can potentially be resolved by modifying the design of the window assembly as shown in Figure 82. The new design can reduce turbulences and perhaps create a parallel uniform flow downstream from the window.

Figure 82. Parallel uniform flow configuration.

**Appendix A Topical Report Task 1 Real Time Flame Monitoring of Gasifier
Burner and Injectors, Task 1 (Year 1)**

Real Time Flame Monitoring of Gasifier Burner and Injectors

Task 1 (Year 1) – Laboratory Sensor Development

**Topical REPORT
(April 2003)**

**Prepared by
James Servaites
Serguei Zelepouga
David Rue**

**Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, IL 60018**

GTI Project No. 61162

DOE Project Manager

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Executive Summary

This report is submitted to the United States Department of Energy in partial fulfillment of the contractual requirements for Phase I of the project titled, “Real Time Flame Monitoring of Gasifier Burner and Injectors”, under co-operative agreement number **DE-FS26-02NT41585**. The project is composed of three one-year budget periods. The work in each year is divided into separate Tasks to facilitate project management, orderly completion of all project objectives, budget control, and critical path application of personnel and equipment. Work planned for Task 1 (Year 1) was conducted with laboratory gas-air and natural gas / oxygen enriched air burners and a laboratory prototype of the Gasifier optical sensor. This Topical Report presents results of the Task 1 work. The optical sensor was used to monitor selected UV and visible wavelengths to collect accurate flame characterization information regarding mixing, flame shape, and flame fuel rich and fuel lean zones. Flame richness, for example, was determined using OH and CH intensity peaks in the 300 to 500 nanometer range of the UV and visible spectrum.

The laboratory burner was operated over a wide range of air to fuel ratio conditions from fuel rich to fuel lean. The sooty oxygen enriched air flames were established to test the sensor ability to characterize flame structures with substantial presence of hot particles emitting strong “black body radiation”. The knowledge gained in these experiments will be very important when the sensor is used for gasifier flame analyses. It is expected that the sensor when installed on the Global Energy gasifier will be exposed to complex radiation patterns. The measured energy will be a combination of spectra emitted by the combusting gases, hot solid particulates, and hot walls of the gasifier chamber. The ability to separate flame emissions from the “black body emissions” will allow the sensor to accurately determine flame location relative to the gasifier walls and the injectors, as well as to analyze the flame’s structure and condition. Ultimately, this information should enable the gasification processes to be monitored and controlled and as a result increase durability and efficiency of the gasifier.

During the next task (Task 2), a coal gasifier burner test stand will be assembled in the GTI Combustion Laboratory. This scaled-down mock-up of a working gasifier combustion system will provide the flexible platform needed in the second year of the project to test the flame sensor and to determine the changes in flame characteristics that occur as gasifier burners and injectors deteriorate with long-term use.

The test stand will simulate the geometry and operating parameters of coal gasifier burners used by Global Energy. Bench-scale tests will be conducted with the improved sensor and the coal gasifier burner on the stand assembled in Task 2. In this Task, the burner(s) will be operated at optimum conditions. Efforts will focus on obtaining accurate and repeatable flame characteristics including flame shape, mixing, and fuel rich and lean areas of the flame. The sensor hardware will be simplified during this testing period in preparation for industrial testing on a gasifier. Other components needed in industrial tests, including view ports, wiring, etc., will be specified.

Burner Condition Testing will be conducted in the second half of Year 2 of the project. The tests will be conducted with the coal gasifier burner(s) going through cycles from new to completely failing. Flame characteristics will be monitored through the full burner life cycle. Data analysis will be used to determine the specific flame characteristics that correlate with burner deterioration. The sensor will be simplified to measure the specific flame characteristics most related to burner or injector wear.

At the start of the third Project year, the laboratory versions of the flame sensor will be modified for testing on a working coal gasifier operated by Global Energy. Modifications will include making the sensor and computer interface more rugged for industrial operation, selecting appropriate probes, housings, and supports for the sensor in order to have optical access through the burner or the wall, simplifying hardware and connections so the complete sensor package can be transported and installed on site; and designing any needed cooling, optical, or electrical protection. At least one trip will be made to the site by project personnel to determine optimum locations for the sensor. Any needed modifications for access to the combustion chamber or the burner/injector at specific locations will also be made in this Task. The plant modifications to allow sensor access will be made by Global with assistance from GTI personnel.

During the final Task 6 of the project, demonstration testing of the flame sensor will be conducted on a coal gasifier operated by project team member Global Energy. GTI and Global staff will work together to choose the sensor location and to mount the new, optical sensor. A series of three trips is anticipated. UIC personnel will provide assistance in testing and installation as needed. The first trip will focus on installing the instrument and collecting baseline coal gasifier burner operating data. The second trip will focus on collecting data with the sensor at a later period in the operating life of the burner or injector. Finally, a long-term test

will be conducted in which data from the flame sensor is collected over the full four to eight week life of the burner. This data will be reviewed to determine relationships between burner wear and flame characteristics in a working gasifier. Roper Scientific will evaluate sensor performance and guide their deployment with an interest toward potential commercialization of these revolutionary new instruments.

A Final report summarizing work in all three years of this project will be prepared at the end of this Task.

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1.0 Introduction

Combustion scientists and engineers have studied radiant emissions of various flames for many years. Technologists have understood the rich potential for flame sensors to maintain burners at optimum performance, to adjust burners, to decrease emissions of CO and NO_x, to determine burner wear, to precisely turn down burners, etc for some time.

Sensors monitoring broad infrared, visible, and ultraviolet regions are routinely used today to monitor flames. UV and IR sensors are built into flame safety and control. Conventional analog and digital cameras are used to monitor flame shape and length. These sensors allow furnace operators to manually adjust appropriate burner controls to change for example flame length or firing rate as well as to maintain safe and stable combustion.

The sensitivity and design of these sensors makes them incapable of deeper qualitative and quantitative monitoring and analyses of complicated combustion processes occurring for example during coal gasification processes.

The goal of this project is to develop a sensor that goes beyond the capabilities of all existing combustion sensors. The flame characteristics monitored by this sensor will be flame shape, flame mixing patterns, flame rich/lean zones distribution, and hydrocarbon oxidation dynamics. This information should provide reliable information on the wear of coal gasifier burners and injectors as well as helping to improve the overall understanding of gasification processes. That information will allow gasifier operators to plan for burner replacement and thereby increase gasifier reliability and save money. The sensor data on real flame characteristics will also enable burner designers to build better, longer-lasting burners, which will also lead to gasifier operation savings.

2.0 Objective

The project objective is to develop a reliable, practical, and cost effective means to monitor coal gasifier burner and injector flame characteristics and accurately predict burner wear and need for replacement using a modified version of an optical flame sensor under development at GTI. Specific objectives include:

- Modify a developmental GTI flame characteristic sensor for gasifier burners and injectors,
- Assemble and test the flame characteristics sensor on laboratory air-gas flames and bench-scale simulated air-coal gasifier burner flames,
- Determine the optimum sensor positions relative to a coal gasifier burner flame and select the best flame characteristics to accurately determine burner wear,
- Install the flame characteristics sensor to monitor a gasifier burner or injector,
- Monitor a coal gasifier burner flame through a full life cycle and correlate measured flame characteristics with burner conditions and wear.

3.0 Scope of Work

This project includes modification of a developmental stage GTI optical flame sensor to serve as a flame characteristics sensor for burners and injectors on coal gasifiers. Work will begin with measuring flame characteristics including mixing patterns, flame shape, and flame fuel rich and fuel lean regions for laboratory air-gas flames and determining the best positions to make these measurements. A coal gasifier burner test stand will be assembled, and work in the second project year will focus on correlating flame characteristics measurements with burner performance and burner deterioration from wear. Finally, a simplified, industrially-robust flame characteristics sensor will be installed on a Global Energy coal gasifier and the burner performance measurements will be correlated with burner wear. At the completion of the project, the project team will have developed a sensor and sensor data protocol to monitor coal gasifier burner performance that is able to predict burner deterioration and imminent failure and need for replacement. A summary of the Tasks to be performed to complete this Scope of Work, the Schedule of Tasks, and the project Major Milestones are presented below.

Tasks to be Performed

The project will be conducted in 36 months, composed of three one year budget periods.

The work in each year is divided into separate Tasks to facilitate project management, orderly completion of all project objectives, budget control, and critical path application of personnel and equipment. Work planned for each project year and each Task is summarized below.

Task 1 (Year 1) – Laboratory Sensor Development

Work in this Task will be conducted with laboratory gas-air burners and extended versions of the optical sensor already in development at GTI. The optical sensor will monitor selected UV, visible, and/or near-IR wavelengths to collect accurate flame characterization information regarding mixing, flame shape, and flame fuel rich and fuel lean zones. Flame richness, for example, will be determined using OH and CH intensity peaks in the 300 to 500 nanometer range of the UV and visible spectrum.

Laboratory burners will be operated over a wide range of firing conditions from fuel rich to fuel lean and over a range of deteriorating burner conditions. Sensors will be placed in a number of positions around the flame to learn the best locations to acquire flame characteristics information. GTI, with UIC assistance, will collect the data and correlate flame characteristics with burner condition. The team will determine preferred physical sensor positions relative to the burner. Also, the sensor will be improved based on testing results to provide the needed flame characteristics data. This information will be used during bench-scale testing in Tasks 3 and 4 in Year 2.

Task 2 (Year 1) – Gasifier Burner Stand Assembly

A coal gasifier burner and injector test stand will be assembled in the GTI Combustion Laboratory with assistance of UIC students. This scaled-down mock-up of a working gasifier combustion system will provide the flexible platform needed in the second year of the project to test the flame sensor and to determine the changes in flame characteristics that occur as gasifier burners and injectors deteriorate with long-term use.

The test stand will simulate the geometry and operating parameters of coal gasifier burners used by Global Energy. The burners will be fired with the same coal and coal-air ratios used in operating burners. Multiple positions will be available for sensor placement and testing. Every effort will be made to make this stand as flexible as possible and as representative of a larger gasifier burner as possible.

Task 3 (Year 2) – Bench-Scale Sensor Testing

Bench-scale tests will be conducted with the improved sensor and the coal gasifier burner on the stand assembled in Task 2. In this Task, the burner(s) will be operated at optimum conditions. Efforts will focus on obtaining accurate and repeatable flame characteristics including flame shape, mixing, and fuel rich and lean areas of the flame. Multiple sensor positions will be used to learn if the optimum locations determined in Task 1 need to be changed for coal gasifier burners.

The sensor hardware will be simplified during this testing period in preparation for industrial testing on a gasifier. Other components needed in industrial tests, including a view port, cooled periscope, wiring, etc., will be specified.

Task 4 (Year 2) – Burner Condition Testing

Tests will be conducted with the coal gasifier burner(s) going through cycles from new to completely failing. Flame characteristics will be monitored through the full burner life cycle. Data analysis will be used to determine the specific flame characteristics that correlate with burner deterioration. The sensor will be simplified to measure the specific flame characteristics most related to burner or injector wear.

Task 5 (Year 3) – Preparation for Gasifier Testing

At the start of the third Project year, the laboratory versions of the flame sensor will be modified for testing on a working coal gasifier operated by Global Energy. Modifications will include making the sensor and computer interface more rugged for industrial operation, selecting appropriate probes, housings, and supports for the sensor in order to have optical access through the burner or the wall, simplifying hardware and connections so the complete sensor package can be transported and installed on site; and designing any needed cooling, optical, or electrical protection. At least one trip will be made to the site by project personnel to determine optimum locations for the sensor. Any needed modifications for access to the combustion chamber or the burner/injector at specific locations will also be made in this Task. The plant modifications to allow sensor access will be made by Global with assistance from GTI personnel.

Task 6 (Year 3) – Gasifier Flame Sensor Testing

Demonstration testing of the flame sensor will be conducted on a coal gasifier operated by project team member Global Energy. GTI and Global staff will work together to choose the sensor location and to mount the new, optical sensor. A series of three trips is anticipated. UIC

personnel will provide assistance in testing and installation as needed. The first trip will focus on installing the instrument and collecting baseline coal gasifier burner operating data. The second trip will focus on collecting data with the sensor at a later period in the operating life of the burner or injector. Finally, a long-term test will be conducted in which data from the flame sensor is collected over the full four to eight week life of the burner. This data will be reviewed to determine relationships between burner's wear and flame characteristics in a working gasifier. Roper Scientific will evaluate sensor performance and guide their deployment with an interest toward potential commercialization of these revolutionary new instruments.

A Final report summarizing work in all three years of this project will be prepared at the end of this Task.

4.0 Deliverables

Project status reports will be submitted to sponsors on a timely basis. The anticipated reports include quarterly reports and Topical reports at the end of each Task, and a Final report. The quarterly reports, as specified by DOE, will be the Federal Assistance Management Summary Report and the Federal Assistance Program/Project status reports. Topical reports will be prepared at the end of the first and second project years. The first Topical report will describe laboratory results of testing to develop the optical flame sensor for coal gasifier burners. The second Topical report will describe laboratory testing with laboratory versions of flame sensors fabricated based on knowledge presented in the first Topical report. Also included in the second Topical report will be a discussion of the anticipated means to use the flame sensor in a working coal gasifier. The Final report for the project will summarize the results presented in the two Topical reports and will describe the field testing arrangements, sensor, and results related coal burner wear to flame characteristics at a Global coal gasifier.

5.0 Project Schedule and Major Milestones

The six tasks are scheduled to be completed over a 36-month period as shown in the bar chart. The nine major milestones listed below the bar chart will provide project managers and sponsors the means to assess project progress. Each Task contains at least one major milestone.

Table 1 Project Schedule

		Year 1					Year 2				Year 3			
Task		0	3	6	9	12	15	18	21	24	27	30	33	36
1	Laboratory Sensor Development	1 2												
2	Gasifier Burner Stand Assembly													
3	Bench-Scale Sensor Testing													
4	Burner Condition Testing													
5	Preparation for Gasifier Testing													
6	Gasifier Flame Sensor Testing													

Table 2 Major Milestones

1	Lab Sensor Set-Up Complete
2	Sensor Verified on Lab Burners
3	Gasifier Burner Stand Complete
4	Sensor Verified on Bench-Scale Burner
5	Sensor Correlated with Burner Condition
6	Field Test Set-Up Complete
7	Field Testing of Sensor
8	Long-Term Sensor Testing Complete
9	Final Report Prepared

6.0 Discussion

This Topical report presents results of work conducted in the first six months of Task 1 leading up to the first milestone. A laboratory-scale version of the flex-flame burner was designed, fabricated and installed in the GTI Combustion Laboratory. This burner can be fired at rates of 0.02 to 0.4 MMBtu/h. The burner was designed to allow adjustment of flame shape, flame length, and mixing patterns. This burner was tested along with the optical flame sensor also developed at GTI and coupled with the flex flame burner. Besides the burner and the sensor, the developed Flex Flame experimental set up included controls from MKS Inc and a PC based data acquisition system.

Figure 1. Schematic of Experimental Setup

Figure 2. Laboratory showing burner and optical flame sensor

Figure 3. Laboratory optical flame sensor

Utilizing a lens-monochromator-CCD camera system of optics (constituting a sensor), it was possible to map the spectral characteristics of the flames generated from the burner tested (see figures 1 through 3). This sensor is capable of outputting a two-dimensional array containing spectral information on one axis and spatial information on the other axis. The profiles of the flame analyzed were varied by utilizing a mechanical positioning system. Through a series of data acquisition maneuvers, the flame height position changed while a spectral image was captured at each increment. This was performed at one-inch intervals for up to eight inches from the base of the burner. The burner tested is a vertically mounted nozzle-mixed burner specially designed with a quartz mixing nozzle and a containment quartz tube for means of optical probing.

Figures 4 and 5 show example spectra which have been acquired from flames at 10% excess oxidizer with 21% O₂ (air) and 28% O₂, respectively. Flame spectra were collected at flame heights from 1 to 8 inches in one-inch increments. Figures 4 and 5 are shown to portray the key features of the two types of flames and the background radiation subtraction technique that was utilized. The 21% O₂ spectra in Figure 4 was acquired at a flame height of 4 inches. This is the approximate height for peak chemiluminescent light emission. Figure 5 shows a spectrum obtained at a height of 7 inches. This flame produced a significant amount of blackbody radiation at higher locations of the flame. Despite this interference, the data for the CH radical emission spectrum can be distinguished on top of the large amount of blackbody radiation. Also on both Figures 4 and 5, a large amount of continuum radiation can be seen reaching into the deep UV (i.e. below 300 nm). This radiation is due in part to continuous CO₂ light emission.

Figure 4. Background subtraction method, 10% excess air, 21% O₂, 4in

Figure 5. Background subtraction method, 10% excess air, 28% O₂, 7in

A software program has been developed by GTI that is able to identify background radiation, subtract this background, and portray corrected key spectral features. Figures 4 and 5 are screen-shots from this program. Labeled on the screen-shots are the user-specified background limits, the user-specified integration limits, and the background that was subtracted from the spectrum. The background limits are wavelength points on the spectrum where there should be no light emission originating from spectral features of interest. Between the background limits, the background light emission is assumed to be linear over short intervals of the spectra. An interpolation between the background limits gives the radiation that is then subtracted to provide 'clean' data without background radiation interference. The integration limits are used to specify the region of interest on the spectrum where the spectral features are to be integrated for quantitative purposes.

Figures 6 through 9 are the resulting OH and CH radical profiles after processing through the background-subtraction program. Figures 6 and 7 show data collected from a methane-air flame with 10% excess oxidizer, while figures 8 and 9 show data collected from a methane-air-oxygen flame with 10% excess oxidizer and 28% O₂. The flame photos in each figure give a graphical representation of the location at which the data was acquired for the two flame types. The photos in figures 8 and 9 show a much brighter yellow flame generated by the large amounts of soot produced. The plots shown on all four figures represent only the chemiluminescent light emission from the OH and CH radicals.

The software tool for background light subtraction can be extended to the gasification field with some adjustment. The spectral features which are to be isolated are going to be different due to the different chemical properties from methane flames, but the principle remains the same for purposes of blackbody radiation subtraction.

Figure 6. 21% O₂, 10% excess air OH emission profiles

Figure 7. 21% O₂, 10% excess air CH emission profiles

Figure 8. 28% O₂, 10% excess air OH emission profiles

Figure 9. 28% O₂, 10% excess air CH emission profiles

7.0 Conclusions and Recommendations

Test results with the laboratory flame provide the background information needed to extend work toward the second and third project milestones. The project team has met the first milestone on time and budget and is immediately beginning work toward the next milestones.

The OH and CH radical profiles provide valuable information on flame structure and rich/lean flame characteristics. The ratio of OH to CH radical intensities provides the best measurement of flame characteristics. These ratios are shown in Figures 10 and 11 for the 10% excess oxidant flames using air (21% O₂) and oxygen-enriched air (28% O₂).

Comparison of the OH/CH ratios shown in Figures 10 and 11 shows significant difference in the flames structure. The natural gas – air flame has a well-defined hollow cylinder like leaner-combustion zone located directly above the air nozzles of the burner. On the other hand, the natural gas oxygen-enriched flame has a richer flame zone located in the middle of flame. The flame becomes richer towards the walls of the mixing nozzle. Also, a more defined rich and lean zone indicates a stiffer flame and more intense mixing. Obtaining this type of flame characteristics information in real time with a coal gasifier flame is the overall objective of this project. The project team has now demonstrated that the sensor can acquire this type of information in real time with sooty natural gas flames in the laboratory. Work will now proceed toward modifying and extending the hardware, software, support equipment, and techniques to work with large-scale coal gasifier flames.

Figure 10. OH/CH Ratios for 21% O₂ Flame

Figure 11. OH/CH Ratios for 28% O₂ Flame

**Appendix B Topical Report Task 1 Real Time Flame Monitoring of Gasifier
Burner and Injectors, Task 1 and 2 (Year 1)**

Real Time Flame Monitoring of Gasifier Burner and Injectors

Task 1 and 2 (Year 1) – Laboratory Sensor Development

**Topical REPORT
(October 2003)**

**Prepared by
James Servaites
Serguei Zelepouga
David Rue**

**Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, IL 60018**

GTI Project No. 61162

DOE Project Manager

October 2003

Executive Summary

This report is submitted to the United States Department of Energy in partial fulfillment of the contractual requirements for Phase I of the project titled, “Real Time Flame Monitoring of Gasifier Burner and Injectors”, under co-operative agreement number **DE-FS26-02NT41585**. The project is composed of three one-year budget periods. The work in each year is divided into separate Tasks to facilitate project management, orderly completion of all project objectives, budget control, and critical path application of personnel and equipment. This Topical Report presents results of the Task 1 and 2 work. The 2 D optical sensor was developed to monitor selected UV and visible wavelengths to collect accurate flame characterization information regarding mixing, flame shape, and flame rich/lean characteristic. Flame richness, for example, was determined using OH and CH intensity peaks in the 300 to 500 nanometer range of the UV and visible spectrum.

The laboratory burner was operated over a wide range of air to fuel ratio conditions from fuel rich to fuel lean. The sooty oxygen enriched air flames were established to test the sensor ability to characterize flame structures with substantial presence of hot solid particles emitting strong “black body radiation”. The knowledge gained in these experiments will be very important when the sensor is used for gasifier flame analyses. It is expected that the sensor when installed on the Global Energy gasifier will be exposed to complex radiation patterns. The measured energy will be a combination of spectra emitted by the combusting gases, hot solid particulates, and hot walls of the gasifier chamber. The ability to separate flame emissions from the “black body emissions” will allow the sensor to accurately determine flame location relative to the gasifier walls and the injectors, as well as to analyze the flame’s structure and condition. Ultimately, this information should enable the gasification processes to be monitored and controlled and as a result increase durability and efficiency of the gasifier.

To accomplish goals set for Task 2 GTI will utilize the CANMET Coal Gasification Research facility. The Entrained Coal Gasifier Burner Test Stand has been designed and is currently under construction in the CANMET Energy Technology Center (CETC), the research and technology arm of Natural Resources Canada (NRCan). This Gasifier Burner Stand (GBS) is a scaled-down mock-up of a working gasifier combustion system that can provide the flexible platform needed in the second year of the project to test the flame sensor. The GBS will be

capable of simulating combustion and gasification processes occurring in commercial gasifiers, such as Texaco, Shell, and Wabash River.

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Introduction

Combustion scientists and engineers have studied radiant emissions of various flames for many years. Technologists have understood the rich potential for flame sensors to maintain burners at optimum performance, to adjust burners, to decrease emissions of CO and NO_x, to determine burner wear, to precisely turn down burners, etc for some time.

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The goal of this project is to develop a sensor that goes beyond the capabilities of all existing combustion sensors. The flame characteristics monitored by this sensor will be flame shape, flame mixing patterns, flame rich/lean zones distribution, and hydrocarbon oxidation dynamics. This information should provide reliable information on the wear of coal gasifier burners and injectors as well as helping to improve the overall understanding of gasification processes. That information will allow gasifier operators to plan for burner replacement and thereby increase gasifier reliability and save money. The sensor data on real flame characteristics will also enable burner designers to build better, longer-lasting burners, which will also lead to gasifier operation savings.

Objective

The project objective is to develop a reliable, practical, and cost effective means to monitor coal gasifier burner and injector flame characteristics and accurately predict burner wear and need for replacement.

Scope of Work

This project includes modification of a developmental stage GTI optical flame sensor to serve as a flame characteristics sensor for burners and injectors on coal gasifiers. Work will begin with measuring flame characteristics including mixing patterns, flame shape, and flame fuel rich and fuel lean regions for laboratory air-gas flames and determining the best positions to make these measurements. A coal gasifier burner test stand will be assembled, and work in the second project year will focus on correlating flame characteristics measurements with burner performance and burner deterioration from wear. Finally, a simplified, industrially-robust flame characteristics sensor will be installed on a Global Energy coal gasifier and the burner performance measurements will be correlated with burner wear. At the completion of the project, the project team will have developed a sensor and sensor data protocol to monitor coal gasifier burner performance that is able to predict burner deterioration and imminent failure and need for replacement. A summary of the Tasks to be performed to complete this Scope of Work, the Schedule of Tasks, and the project Major Milestones are presented below.

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Project Schedule and Major Milestones

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Table 1. Project Schedule

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Table 2. Major Milestones

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2	Sensor Verified on Lab Burners
3	Gasifier Burner Stand Complete
4	Sensor Verified on Bench-Scale Burner
5	Sensor Correlated with Burner Condition
6	Field Test Set-Up Complete
7	Field Testing of Sensor
8	Long-Term Sensor Testing Complete
9	Final Report Prepared

Discussion

This Topical report presents results of work conducted in the second six months of Task 1 leading up to the second milestone. The report also introduces work conducted according to the Task 2 leading to the milestone 3.

Gasifier Burner Stand Assembly

(The gasifier burner stand diagram and its description is reproduced from “Renovation Of CETC Pressurized Gasification Pilot Plant”, DENNIS Y. LU, EDWARD J. ANTHONY AND MICHAEL BURKE; CANMET Energy Technology Center, Natural Resources Canada)

The Gasifier Burner Stand Assembly has been designed and is currently under construction at the CANMET Energy Technology Center (CETC), the research and technology arm of Natural Resources Canada (NRCan).

Figure 1. Entrained Flow Gasifier

Entrained bed gasifiers employ pulverized coal. Fine particles ensure high gasification rates which are crucial for achieving high temperatures at short residence times, resulting in low levels of tars and heavy hydrocarbons in the gas products. High temperatures are required to achieve slagging conditions. The slag is a non-leachable, glass-like material, which can be disposed of safely. The slagging propensity of coal's mineral matter influences operating conditions and the design of process equipment. A minimal temperature limit must be maintained in order to achieve slagging conditions. In general, all coal ash with softening temperature lower than 1250°C under reducing conditions is withdrawn from the gasifier as a slag. If the softening temperature is higher than 1450°C most of the ash would be in a dry form unless a fluxing agent is added to the coal to decrease the softening temperature.

Table 3. Pressurized Gasifier Specifications

Parameter	Units	Design Value	Max. Value
Gasifier operating pressure	MPa	1.5	1.8
Gasifier operating temperature	°C	1400	1800
Gasifier shell temperature	°C	100	150
Dry feed rate (@ 70% -200 mesh, 30% -100 mesh)	kg/h	20	25
Dry feed pressure	MPa	1.5	1.8
Slurry feed rate (@ 60-70% solids in water)	kg/h	30	40
Slurry feed pressure	MPa	1.5	1.8
Primary O ₂ rate	kg/h	12	30
Primary O ₂ temperature	°C	150	150
Secondary O ₂ rate	kg/h	12	30
Secondary O ₂ temperature	°C	500	500
Steam rate	kg/h	30	60
Steam temperature	°C	500	500
Quench water rate	L/min	10	10
Quench vessel shell temperature:	°C	160	240
Igniter NG rate	SLPM	25	25
Igniter NG pressure	psig	20	20
Burner NG rate	SLPM	45	45
Burner NG pressure	psig	20	20

CETC's pressurized gasifier is a cylindrical, vertical, single zone, downflow refractory-lined configuration with reactant injection at the top and ash and gas withdrawal at the bottom. The reactor, which is assembled from a total of five fabricated segments, is 127 mm in I.D. and 1524 mm in height. The top segment mounting the injection system and burner has a viewport with sight glass assembly as well as cooling coils. The refractory lining (100 mm) is resistant to high temperatures in the reactor (1400-1800°C), as well as resistant to liquid slag in both oxidizing and reducing zones. It is physically resistant to abrasive actions of high-velocity particles and must conduct a minimum amount of heat through the shell, which is kept lower than 150°C during operation.

The reactor exit segment consists of a blind flange welded to accommodate tangentially entering water cooling jets. The water quench used to cool gas and to solidify the slag is located at the gas exit piping.

Solid Fuel Feeding

The dry solid fuel hopper is a pressure vessel with a capacity of 100 kg. Fuel, i.e. pulverized coal is loaded into the hopper via a 200 mm diameter opening in the top of the pressure vessel. Once fully charged, the opening is sealed and the vessel is pressurized with nitrogen to the desired level. The pulverized coal is withdrawn by a 25 mm variable speed auger to a pickup point where it is entrained in nitrogen and carried through a 9.5 mm tube to the reactor. Two agitators are installed to maintain a constant feed density at the auger (intromitter auger encircling the feed auger) and to eliminate bridging in the hopper (stirrer). Several 6 mm "coal bed fluffing lines" have also been installed in the bottom of the hopper in an effort to reduce the tendency of the coal bed to compact under its own weight. The instantaneous coal feed rate is measured using a load cell. The slurry feed module is capable of delivering 15 to 40 kg/h of slurry feed at a solids content up to 65%. The slurry is pumped to the gasifier feed nozzle using two progressing cavity pumps; a recirculation pump which helps to ensure good mixing is maintained and a dosing pump with a variable speed driver to deliver the slurry to the gasifier. A slurry tank, with a maximum capacity of 850 L, is open to atmosphere and employs a mixer attached to the top of the tank is used to continuously stir the slurry mixture. The upstream feed flowrate is calculated from the sampling time and the volumes of slurry samples and dried solids. The downstream flowrate to the gasifier is measured by a magnetic flowmeter, and controlled by the speed driver of the dosing pump.

Gas and Steam Feeding

Oxygen is supplied from a bank of 12 high-pressure (12.4 MPa) gas cylinders. A pressure regulator reduces the pressure before the distributor to individual control valves in the primary and secondary trains. Primary oxygen is preheated with a 3.15 kW electric circulating heater and the secondary oxygen is preheated by two serial 3.75 kW heaters. Check valves and pressure safety valves are provided in each line for system safety. Steam is supplied by a 60 kW electric boiler, providing a maximum of 60 kg/h of saturated steam at 3.0 MPa. Insulation is required to prevent any condensation before the steam enters the control valve and the 17 kW superheater. The steam and secondary oxygen then flow together to the secondary inlet of the

gasifier. Natural gas is used for preheating the reactor to the desired temperature before introducing the solid fuels. The burner incorporates inlets for coaxial primary and secondary streams, a swirl generator for the secondary stream, an igniter preheat burner. The swirl generator consists of two rating plates with adjustable vanes that impact radial velocity components of the secondary stream. The characteristics of the swirl are controlled by adjusting the positioning of the vanes. The start-up burner heats the gasifier to 800-900°C before coal or coke fuel can be fed into the reactor to further raise the temperature to a desired level. Then the system is switched to gasification mode. Since the rated pressure of the natural gas network is only 0.115 MPa, the burner can only be used before pressurizing the system. Helium/nitrogen are used as tracers as well as in pressurizing and fluffing the coal hopper, and as the coal entraining gas. Both gases are supplied in standard cylinders and controlled by regulators and control valves.

Flue Gas Quench and Particulates Removal

The exit at the bottom of the gasifier is the water quench system. The water requirements will be in the range of 10 L/min to maintain the shell temperature of the quench vessel lower than 240°C. Large slag chunks will remain in the quench vessel and be discharged when the run is completed. The product gas will be further quenched in the venturi scrubber (15 L/min water injection). The water is from the same pump that provides water to the quench vessel. The temperature of the flue gas will be as low as 30-50°C after the two-stage quench. Besides further cooling the flue gas, the venturi scrubber also plays a significant role in particulates removal. The particulate removal efficiency of 95% is expected to be captured in the scrubber. Cleanup is at temperature up to 500°C by bypassing the quench vessel, scrubber and cyclone demister. Gas exiting the condenser passes through the gas filters to remove particulates larger than 3 microns before the gas pressure control valve. Atmospheric exhaust from the regulator joins the gas products from the liquid filtration system. The combined gas stream passes sequentially through the knockout tank for acid-gas dissolution and further removal of small droplets before entering the flare stack. Prior to the knockout tank, a portion of the gas flow is extracted to the sampling apparatus. After passing through a fine polishing filter, the sample gas is analyzed on-line with a multi-component mass spectrometer (Hamilton and Sundstrand MGA 1600ES) capable of measuring concentrations of up to 16 chemical species at an interval of seconds. The wastewater from the quench vessel, venturi scrubber and condenser is collected in a drain vessel for

subsequent water treatment. The quench water and solid residues are also sampled and analyzed. The quenched gas products enter the condenser after leaving the cyclone demister. The condenser is necessary in case a power failure prevents the water pump from providing quench water for cooling the flue gases, as well as cooling moderately hot gas

Sensor Development

In the last topical report we described our approach to background light subtraction in gasifier environments and showed data of this technique using a natural gas burner constructed with quartz components to allow for full optical access. The sensor used in the first phase of research, outlined in the last topical report, consisted of a CCD camera, monochromator, and UV lens (see figure 2). This sensor was useful for detailed optical analysis of flames and observation of the radicals present. This preliminary sensor was, however, only capable of extracting optical data in one dimension. The last topical report presented maps of radicals in several flames where the flame was moved incrementally to observe the flame at many locations.

In order to generate a much more detailed map of the radicals being generated within a gasifier and also to considerably reduce the data acquisition time, GTI developed a two-dimensional sensor that consists of significantly different hardware and software. The prototype of the 2-D sensor is shown in figure 3. Here the sensor is shown to consist of a CCD camera, filter-wheel, and a UV lens. The CCD camera used here is much more sensitive than the one used previously to allow for shorter camera exposure times, since six images must be collected, one through each of the six filters mounted in the filter-wheel. The filter-wheel replaces the monochromator of the previous sensor. The filter-wheel consists of six carefully chosen filters, enabling subtraction of background radiation while preserving the radiation given from two different radicals when coupled with a GTI-developed software program. The lens used here is more sensitive in the UV region of the spectrum allowing for less camera exposure time. Figure 4 shows the sensor as it is positioned in the laboratory for testing of the natural gas burner.

As mentioned above, the filter selection for the sensor is crucial. By utilizing data acquired using the first one-dimensional sensor (figure 2), filters were selected based on the flame spectra. Figure 5 shows a natural gas flame spectrum obtained experimentally with the filter center locations displayed. The red lines show the locations of the filters that are used for subtraction of the background light emission. The blue lines signify the locations of the filters used for acquisition of the radical light, here OH^* and CH^* . The pink lines superimposed onto

the spectrum roughly signify the light subtracted by the computer program algorithm during data processing.

In the previous topical report we used oxygen enrichment to create flames of various conditions and different amounts of soot (i.e. background light). In this study, flame conditions were varied only by adjusting the air nozzle sizes. The test burner is designed with removable nozzles which were varied between 0.18 in. and 0.32 in. . All other flame conditions were held constant during testing and the flames were run at 0% excess air. The flames with the smaller air nozzles have a much faster velocity flame and thus better mixing. This increased mixing results in a very short, compact flame with very little soot (see figure 6 (a)). The flames with the larger air nozzles give a flame that is much slower and portrays very poor mixing. These slow flames generate significant amounts of soot (see figure 6 (b)) and very different spectra to observe with the sensor.

The preliminary data that has been acquired and processed is shown in figure 7. Images in figure 7 (a), (b), (c), and (d) are all shown normalized to the peak intensity of each image (i.e. the intensities are not relative to one another). The spatial sizes are the same in all images. The flame with 0.18 in. air nozzles is portrayed as a shorter, wider flame with the OH* intensities extending slightly further up than the CH*. The 0.32 in. air nozzles generate a flame that is much taller and narrow. The key feature here is the soot background subtraction, which the software does nicely if you notice how the CH* intensity drops off at the top of the image, rather than further increasing where the background radiation is strongest. The OH* emission image here shows a slight drop off after the primary flame zone and then another increase in the emission intensity. This second increase in OH* emission is due to known secondary reactions in the flame that produce OH* emission. The images shown in figures 7 (e) and (f) are an example of data processing of the other two images. Certain flame features are sometimes clearer when the ratio of two radicals is examined. These two images shown are the same scales.

Figure 2. 1-D Optical Sensor Consisting of CCD Camera, Monochromator, and Lens.

Figure 3. 2-D Optical Sensor Consisting of CCD Camera, Filter-Wheel, and Lens.

Figure 4. 2-D Optical Sensor Positioned for Data Acquisition From the Test Burner.

Figure 5. Natural Gas Flame Spectrum Showing the Six Filter Center Locations and the Subtracted Background Radiation (in pink).

(a) 0.18in. air nozzles

(b) 0.32in. air nozzles

Figure 6. Flame Photographs From the Test Burner Running at 0% Excess Air.

(a) OH*, 0.18in. nozzle

(b) OH*, 0.32in. nozzle

(c) CH*, 0.18in. nozzle

(d) CH*, 0.32in. nozzle

(e) OH*/CH*, 0.18in. nozzle

(f) OH*/CH*, 0.32in. nozzle

Figure 7. OH*, CH*, and OH*/CH* Images From Flames of 0% Excess Air (nozzle size shown).

Conclusions and Recommendations

The sensor has been demonstrated to work on natural gas flames with background radiation (soot also produces background radiation). The second version of the sensor is capable of acquiring and processing two-dimensional images, by utilizing a non-dispersive spectrographic technique (filter wheel). A site at CANMET has been identified as optimum for testing the sensor on a coal burner similar to the type used in the Wabash River gasification unit.

Work next quarter will continue in three areas.

- Continued development of flame properties recognition algorithms and algorithm implementation in the necessary data analysis software. .
- Hardening of the sensor for demonstration testing. This will involve assembling an enclosure for the camera and filter wheel. The enclosure is expected to be water-cooled for added hardware protection.
- Finally, the third effort next quarter will focus on working with CANMET to define the scope of needed simulated gasifier tests. This will include test conditions, optical access locations, equipment needs, access requirements, and intellectual property protection. Global Energy engineers will help to specify the test conditions (coal, temperature, slurry properties, pressure, etc.).

**Appendix C Topical Report Task 3 Real Time Flame Monitoring of Gasifier
Burner and Injectors, Task 3**

Real Time Flame Monitoring of Gasifier Burner and Injectors

Task 3 –

Topical REPORT

Prepared by

**Serguei Zelepouga
Vasilios Soupos**

**Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, IL 60018**

GTI Project No. 15337

**DOE Project Manager
Jenny Tenant**

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Executive Summary

This report is submitted to the United States Department of Energy in partial fulfillment of the contractual requirements for Phase I of the project titled, “Real Time Flame Monitoring of Gasifier Burner and Injectors”, under co-operative agreement number **DE-FS26-02NT41585**.

This Topical Report presents results of the work effort under Task 3 as well as a brief discussion of the results of previous tasks as they relate to current work.

To accomplish the goals set for Task 3 GTI utilized the CANMET Vertical Combustor Research Facility (VCRF). The testing conditions of the Vertical Combustor were selected to simulate possible instabilities and temperature variations typical for coal fired gasifiers. Task 3 was added at a later date to the overall scope of the project after the completion of Tasks 1 and 2. The reason for adding Task 3 was to conduct sensor testing on a simpler, more flexible atmospheric coal combustion platform. The test data obtained from the atmospheric unit support many of the modifications to the sensor algorithm and hardware needed for the sensor to function correctly in a pressurized gasifier. A more detailed justification for adding Task 3 to the project is presented in the section “Work Effort and Justification for Task 3” presented later in this report.

During the next tasks (Task 4 and 5), GTI will utilize the CANMET Energy Technology Center (CETC) Pressurized Entrained Flow Gasifier. Based on the results of the tests on the pressurized gasifier, the sensor algorithm, hardware and software will be finalized for the field trials.

Finally the sensor will be tested at an industrial scale gasifier such as the ConocoPhillips gasifier at Wabash River Indiana.

Introduction

Technologists have long understood the rich potential of optical flame sensors to maintain burners or coal gasifier injectors at optimum performance, to decrease emissions of CO and NO_x, to determine burner or injector wear, and to precisely turn down and adjust firing rates. Sensors monitoring broad infrared (IR), visible, and ultraviolet (UV) radiation are routinely used today to monitor flames. UV and IR sensors are built into flame safety and control devices. Conventional analog and digital cameras are used to monitor flame shape and length. These sensors allow furnace operators to manually adjust appropriate burner or coal injector controls to change flame length or firing rate as well as to maintain safe and stable combustion. The sensitivity and design of these sensors make them incapable of deeper qualitative and quantitative monitoring and analysis of complicated combustion processes such as coal gasification.

The optical flame sensor currently under development at GTI is expected to extend the capabilities of the existing combustion sensors. This sensor not only registers the presence of UV or IR light, but also monitors flame properties and flame position relative to the injector by collecting spatially resolved spectroscopic images of the flame light. The high temperatures and the chemically active environment present in flames produce a number of excited species. Emission signatures of these species can be an effective tool for real-time active control systems and diagnostic sensors.

UV and IR emission spectroscopy have been recognized as valuable tools for non-intrusive flame temperature, structure, and species analysis. To date, significant progress has been made in understanding the spectroscopic features of gaseous hydrocarbon flames and methane flames in particular. Relatively less attention has been paid to spectroscopic studies of coal combustion.

Objective

The project objective is to develop a reliable, practical, and cost effective means to monitor coal gasifier burner and injector flame characteristics and accurately predict burner wear and need for replacement. The operation of a fuel-rich flame in a gasifier environment requires precise control of gasifier parameters to ensure flame stability and high gasification efficiency. The precise control of the gasifier flows is needed to maintain the flame at rich conditions yet not allow low enough temperatures that would lead to reduced slug viscosity and solidification. Alternatively, operating too close to stoichiometry may result in prohibitively high temperatures and subsequent wear of the burner and refractory.

Scope of Work and Deliverables

This project includes modification of a developmental stage GTI optical flame sensor to serve as a flame characteristics sensor for burners and injectors on coal gasifiers. This R&D effort is divided into seven tasks. In the first task, a developmental GTI flame characteristic sensor was modified to monitor selected UV, visible, and/or near-IR wavelengths to characterize fuel mixing, flame shape, and flame fuel rich and fuel lean zones. The deliverable of task 1 is a topical report describing the modified flame sensor.

In task 2, the flame sensor was tested with specially designed and build laboratory gas-air-oxygen burners. The burners was operated over a wide range of firing conditions from fuel rich to fuel lean and over a range of deteriorating burner conditions. The deliverables of task 2 is a lab-scale test plan and a topical report containing the results of the flame sensor tests including data analysis and conclusions.

Task 3 was added at a later date to the overall scope of the project after the completion of Tasks 1 and 2. A justification for adding Task 3 to the project is presented in the section “Work Effort under Task 3” presented later in this report. In task 3 the sensor was modified for testing at the Vertical Combustor Research Facility (VCRF) at the CANMET Energy Technology Center (CETC). The results of the tests were used to further define the desired test parameters for further testing. Spectrally resolved and video images were collected from stable and unstable flames at nearly “blow off” conditions. The obtained data was analyzed in order to establish the correlation between flame spectral characteristics as well as spatial intensity distribution and flame stability. The deliverables of task 3 are a bench-scale test plan and a topical report containing the results of the flame sensor tests including data analysis and conclusions.

In Task 4 the sensor will be tested at the CETC pressurized entrained flow gasifier (PEFG). Efforts will be focused on obtaining accurate and repeatable flame characteristics including flame shape, mixing, and fuel rich and lean areas of the flame. At this point, the sensor hardware will be simplified to make it more practical, in preparation for testing on an industrial gasifier. Other components needed for industrial tests will be specified, including a view port of cooled periscope, wiring, etc. The deliverables of task 4 are a bench-scale optimum burner condition test plan, a topical report containing the results of the flame sensor tests including data analysis and conclusions, and a description of all modifications made to the flame sensor including design drawings.

Task 5 will focus on conducting tests with the coal gasifier burner going through cycles from new to completely failing. Data analysis will be used to determine the specific flame characteristics that correlate with burner deterioration. Further sensor hardware simplification will follow to measure only the specific flame characteristics most related to burner or injector wear. The deliverables of task 5 are a bench-scale optimum burner condition test plan, a topical report containing the results of the flame sensor tests including data analysis and conclusions, and a description of all modifications.

In Task 6 the flame sensor will be further modified in preparation for testing on a working industrial coal gasifier. Modifications will include making the sensor and computer interface more rugged for industrial operation, selecting appropriate probes, housings, and supports for the sensor in order to have optical access through the burner or the wall, simplifying hardware and connections so the complete sensor package can be transported and installed on site; and designing any needed cooling, optical, or electrical protection. Modify, if needed, access to the combustion chamber or the burner/injector at specific locations.

In Task 7 of the sensor development the sensor will be tested on the selected industrial coal gasifier. The test is intended to acquire coal gasifier burner operation data collected in the beginning, middle and late stages of the life of the burner. The goal of this task is to determine the fundamental relationships between burner wear and flame characteristics in a working industrial gasifier. The deliverables of task 7 are a gasifier flame sensor test plan and a topical report containing the results of the flame sensor tests including data analysis and conclusions.

Results to Date

Task 1 and 2 Results

During Tasks 1 and 2 of the project two laboratory-scale versions of spectroscopic sensors were developed and tested in the GTI combustion laboratory. Both versions utilize similar sensing approaches and hardware configurations. In both units, flame light is first collected with a UV lens and is then processed spectroscopically and projected on a CCD (charged couple device) of a spectroscopic camera. The camera output is digitized and analyzed using data acquisition software and hardware. The first version of the laboratory sensor uses an imaging spectrograph's grating to disperse the light and obtain light intensity distribution as a function of the wave length. This sensor configuration allows acquiring high definition continuous flame spectra in one dimension. In order to scan an entire flame with the 1-D sensor multiple sampling is required. The 1-D sensor version was necessary while the sensor algorithm was still under development and spectral information had to be analyzed in its entirety. The second configuration uses a filter wheel and a set of narrow band filters. This sensor is capable of acquiring two dimensional flame images at selected light wave bands. The disadvantage of this method is limited spectroscopic resolution and range. This sensor is applicable only when the sensor algorithm is developed and the number as well as width of the spectral bands of interest is well established. The photographs of the both sensor configurations are shown in Figure 1 and Figure 2.

Figure 1. 1-D Optical Sensor

Figure 2. 2-D Optical Sensor

Both sensing approaches were tested with a specially designed flex-flame burner in the GTI Combustion Laboratory. The burner is capable of generating flames of variable size and

flame properties. The sensors have been proven to be capable of detecting shape and rich/lean properties of natural gas air/oxygen enriched air flames. The samples of the obtain results are shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7, and Figure 8.

Figure 3 Photo of NG/Air flame

Figure 4 Photo of NG/Oxygen enriched Air flame

Figure 5 OH image captured with 2-D sensor in NG/Air flame

Figure 6 OH image captured with 2-D NG/Oxygen enriched Air flame

Figure 7 OH profiles measured in NG/Air flame with 1-D sensor

Figure 8 OH profiles measured in NG/Oxygen enriched Air flame with 1-D sensor

Work Effort and Justification for Task 3

The pilot-scale pressurized gasifier at CANMET was selected for pilot scale testing of the sensor technology since it the only facility in North America designed to provide flame and gasification conditions similar to conditions generated by industrial entrained pressurized gasifiers such as the ConocoPhillips gasifier at Wabash (the projected site for the commercial-scale tests). However, the CANMET pressurized gasifier is expensive and time consuming to maintain and operate. The mechanical complexity of the pressurized gasifier results in unexpected delays for repairs, maintenance and safety procedures. The tests originally scheduled at the CANMET pressurized gasifier are limited to 6 test conditions due to high cost of access to the gasifier. Each condition was planned to be tested once. Each described test was supposed to take approximately 10 –16 hours to execute due to lengthy startup, transition of one condition to the next and stabilization procedures. It was possible that the scheduled tests could not have been sufficient to collect enough information needed for sensor algorithm modifications. Therefore, it was decided that a significant portion of the needed test data for the sensor algorithm modifications can be obtained by utilizing a simpler, more flexible and easier to operate atmospheric vertical combustor also available at CANMET. Even though the atmospheric combustor is not capable of simulating syngas formation chemistry occurring in a pressurized water slurry gasifier, the structure of the coal flames generated by the atmospheric combustor will be similar to the coal oxygen flame generated by the pressurized unit. Therefore, since flame monitoring (not syngas composition monitoring) is the goal of this project, the test data obtained at the atmospheric unit will support many of the modifications to the sensor algorithm and software needed for the sensor to function correctly in a gasifier. Based on these considerations a new task was added to the project. The goal of this additional task was to establish the coal flame parameters directly affecting flame position, stability, and injector wear. This goal is accomplished by identifying flame spectral features which can be correlated with the unfavorable flame conditions which result in injector wear and process inefficiency.

Experimental Setup and Sensor Modifications

The 1-D sensor was utilized in the pilot scale testing on the VCRF because of the need for highly resolved continuous spectra. The same configuration will be used in future PEFG tests. A new optical interface was developed. The interface allows acquiring images through an observation port as small as 2" in diameter and transferring flame light data at a distance of 30

feet using an optical fiber bundle. Figure 9 is a schematic of the GTI gasifier sensor installed on the Vertical Combustor. The light-collection sensor assembly is attached to the optical access port with a specially designed adapter. The assembly consists of a beam splitter, a 105 mm UV lens, a fiber-optic adapter, and a fiber-optic bundle. The beam splitter divides the collected flame image into two images of the same geometry but lower intensity. The first image is transferred to an imaging spectrograph through a 30-foot fiber optical bundle. The image is spectrally dispersed, recorded, and analyzed. The second image is collected by a digital video camera and is recorded concurrently on a tape and on the hard drive of the data acquisition computer.

The sensor collects a narrow strip of light (light emission profile) and spectrally disperses it on a 256 x 1024 spectroscopic charge-coupled detector (CCD). Therefore, the sensor data acquisition system can produce a two-dimensional array containing spectral information on one axis (intensity per wavelength) and spatial information on the other. Equipped with a 10-fiber fiber bundle the sensor is capable of acquiring and displaying 10 spectra from various flame locations instantaneously.

Figure 9 Multipoint Spectrally Resolved Imaging of the Coal Flame

The geometry and sizing of the optical access is shown in Figure 10. The spectral characteristics of the flame are measured along the flame length using an array of ten optical fibers assembled into an optical fiber bundle as it shown in Figure 10 Optical access dimensions and geometry. The area viewed and analyzed with the GTI sensor is shown in red. The current optical setup is designed for relatively small (in the order of 12") flames generated in the CANMET Pressurized Gasifier and Vertical Combustor. Nevertheless, with some modification to the fiber bundle structure this approach can adapted for flames of any size.

Figure 10 Optical access dimensions and geometry

Figure 11. GTI Gasifier Sensor Mounted on Vertical Combustor at CANMET.

Vertical combustor description

The unit's nominal firing rate is about 0.3 MW. The combustion takes place in a vertically down-fired combustor that has an inside diameter of 1 m (in the top section of the combustor) and an overall length of 8.3 m. The combustor is refractory lined to conserve heat in order to provide a realistic time-temperature history for the burning of coal particles. The primary burner used by the VCRF is a single-register, swirl-stabilized burner developed at CETC-O. The swirl register is a commercial, movable block unit made of carbon steel. The primary stream of this burner (air or CO₂) is admitted into an annulus located within the inner diameter of the swirling secondary stream. The secondary stream consists of ambient air alone or in combination with carbon dioxide (from a bulk storage vessel), or recycled flue gases and oxygen. The amount of oxygen admixed into the secondary stream is limited to less than 28% by volume for safety reasons. Oxygen may also be admitted via a series of holes in the quarrel. There are essentially two types of oxygen combustion that can be generated in the VCRF: air enriched oxygen combustion and O₂/CO₂ combustion. In air enriched oxygen combustion, the oxygen content of the secondary air stream can be increased, effectively raising the flame temperature and altering the flame envelope. The primary air stream, which entrains the

pulverized coal, remains unaltered. In O_2/CO_2 combustion, the primary air is replaced by a stream of CO_2 from the storage vessel and the secondary air stream is replaced with a mixture of oxygen and carbon dioxide. The oxygen content of the secondary stream may be varied from about 21% to 28% by decreasing the amount of CO_2 mixed with the oxygen. The oxygen content may be further increased by direct injection of oxygen at the quarrel permitting the effective oxygen range at the flame to be within 21-42% for O_2/CO_2 combustion and 21-35% for air enriched combustion. In both cases the final maximum allowable oxygen level is set by the maximum allowable refractory lining temperature ($1400^\circ C$) as determined by the measured combustor temperature. The O_2/CO_2 oxidizer mode was selected for our experiments. The goal was to achieve maximum possible concentration of oxygen in the oxidizer stream and as a result maximum flame temperature variation. The flame temperature variation is needed to assess sensor sensitivity to flame temperature variation. The VCRF has three continuous emission monitoring (CEM) systems, which monitor conditions at the mixing plenum preceding the burner, the combustor exit and at the induced draft fan inlet. Species measured include O_2 , CO , CO_2 , SO_2 , NO and NO_2 . During our test the CEM measurements were conducted. The variation of the combustion system parameters used in our experiments did not result any significant changes in the exhaust composition. The large size and high and relatively constant temperature of the combustor and sufficient oxidizer presence insured complete fuel oxidation regardless of flame conditions. Therefore the CEM data will not be presented in this report.

Results

Spectral structures

As pulverized coal is injected in the flame, the coal particle oxidation proceeds through three characteristic stages, or zones; devolatilization, char heating and burning. The relative locations of the corresponding zones in the flame depend on firing conditions such as temperature, feed rates of coal and oxidizers, and other flow parameters such as swirl number. The characteristic flame areas produce emissions of excited CH^* , OH^* , C_2^* and other radicals, line atomic spectra of various metals (Na, K) and black body radiation of heated coal particulates. Each of the flame zones is characterized by specific light emissions. The spatial imaging of the flame allows recognition of the flame structure and relative interposition of the flame zones. This information can be effectively used for control of the flame parameters. Flame parameters including swirl

intensity, coal feed rate, coal feed velocity, and oxygen content in the oxidizer were varied during the trial experiments. These variations led to significant changes in flame geometry and flame stability up to the total flame extinction in the extreme settings. The spectral flame characteristics were recorded in a range of 200 to 800 nm. The characteristic features of the spectra included a strong black body background emitted by the coal flame and the heated refractory walls, chemiluminescent spectra of excited radicals formed in the flame area, and linear spectra of metal atoms present in the supplied pulverized coal feed. Several representative spectra obtained in the conditions of 4 % excess oxygen are depicted. The spectrum of CH* radical is clearly identifiable on the strong blackbody background (Figure 12). The CH* peak is located at vicinity of 430 nm and is approximately 5 nm wide. The CH* peaks of variable intensity were observed in all conducted experiments including rich flames and flames with high coal injection velocities.

Figure 12. Emission Spectrum of Excited CH* Radicals

The characteristic emissions produced by excited OH* were observed in the region of 310 nm (Figure 13). The emissions include a series of ultraviolet bands. The intensity of the peaks varied along the flame length. For a given location, intensity decreased with increased coal supply rate and coal injection velocity.

Figure 13. OH Spectrum

A spectrum of sodium atoms is given as an example of linear spectra observed during the combustion tests. The characteristic Na doublet is located near 590 nm (Figure 14).

Figure 14 Atomic Spectrum of Na

The line shape obtained during the experiments shows an absence of saturation or re-absorption phenomena due to the fact that the studied flames were optically thin. Other intense atomic spectra involve lines of K and Ca.

Selection of Test Points on the VCRF

The experiments on the VCRF were designed to test the flame sensor in order to determine the changes in flame characteristics that occur as gasifier burners and injectors deteriorate with long-term use. The rationale behind each test and how it relates to injector wear is shown in the list below, whereas the detailed results are given in the following sections.

1. **Transition from Natural Gas to Coal:** Natural gas is used to preheat the combustor chamber. The transition tests were conducted to establish the difference in spectral characteristics between coal and natural gas flames.
2. **Coal Feeding Rate Variation:** The situation in which the injector is damaged and fuel and oxygen are not mixing and burning at optimum conditions was simulated by changing the oxygen to coal ratio.
3. **Coal Injection Velocity:** When the injector overheats and warps the fuel injection orifice is likely to reduce in diameter. This will lead to an increased fuel jet velocity. This condition was simulated by increasing the fuel injection velocity.
4. **Swirl Variation:** The secondary air injection angle is intended to enhance the mixing of the secondary combustion air to the primary coal/air stream. Unfortunately, the PEFG currently has no provision for varying the secondary air injection angle. However, these tests on the VCRF were deemed necessary since the majority of industrial gasifiers, including the gasifier operated by ConocoPhillips, do use secondary air injection.

Transition from natural gas to coal

The Vertical Combustor was initially preheated with a natural gas flame for approximately 24 hours. The natural gas fuel was gradually replaced with pulverized coal while keeping the overall fuel mass the same. The flame images in Figure 15, Figure 16, Figure 17, and Figure 18 show the flame visible envelope during transition from NG to coal. The images were obtained by a water cooled camera inserted deep inside the combustor. The radiation

emitted by the natural gas flame (see Figure 15) can not be detected with conventional video cameras. The strong background radiation emitted by the hot refractory overwhelms the flame radiation. When coal is added visible flame radiation increases dramatically. Natural gas visible flame light is a combination of radiations emitted by the hot products (water and carbon dioxide), exited radicals and soot. The visible light emitted by the coal flames also contains radiation from burning coal particles. Hot solid carbon particulates are much better emitters therefore the coal/natural gas and coal flames are much more luminous than natural gas flames.

Figure 15. 20 kg/hr NG

Figure 16. 10 kg/hr NG, 10 kg/hr Coal

Figure 17. 5 kg/hr NG, 15 kg/hr Coal

Figure 18. 0 kg/hr NG, 20 kg/hr Coal

To quantify the OH and CH radiation intensities the OH and CH intensity peaks were integrated and plotted for each tested flame condition (see Figure 19, Figure 20). Figure 19 and Figure 20 show that increasing the coal fraction in the natural gas/coal fuel mixture results in decreasing of OH radical emission while an increase of CH intensity was observed.

Figure 19. CH Intensity

Figure 20. OH Intensity

Figure 21. CH/OH Ratio

Figure 22. Light Intensity at 410 nm

Coal feeding rate variation

In this test, coal injection feed (kg/hr) was incrementally decreased from 20 kg/hr to 10 kg/hr while maintaining the same oxidant level; in this case, atmospheric air. In effect, the coal flame became leaner with each point. Below 10 kg/hr coal feed the flame became too unstable and extinguished. As Figure 23, Figure 24, Figure 25 show, the flame temperature and visible flame light emission decreased with decreasing coal feed. This visual result is verified by the radical species intensity peaks shown in Figure 26, Figure 27, Figure 28, and Figure 29. It is worthwhile noticing that the ratio of CH to OH intensity remained relatively unchanged for fibers 1 and 5. The intensity ratio for fiber number 9 decreased, possibly the result of a shorter flame length.

Figure 23. 20 kg /hr coal

Figure 24. 15 kg/hr coal

Figure 25. 10 kg/hr coal

Figure 26. CH Intensity

Figure 27. OH Intensity

Figure 28. CH/OH Ratio

Figure 29. Light Intensity at 410 nm

Coal injection velocity

The effect of changing the coal injection velocity was examined during this test. The burner utilized in the vertical combustor introduces pulverized coal mixed with air (primary air) inside the combustor. An annular pipe surrounding the primary air/pulverized coal mixture tube introduces secondary air into the combustor to complete the combustion of the coal/air mixture. The coal injection velocity was varied by increasing the delivery pressure of the secondary air stream. As Figure 30, Figure 31, Figure 32, Figure 33 show, increases the coal injection velocity results in the flame being pushed away from the burner mouth creating an unstable flame front at levels 2 and 3. The spectral results shown in Figure 34, Figure 35, Figure 36 indicate that the flame intensity of OH and CH decrease with increasing coal injection velocity. This result can be explained as follows; as the secondary air pressure is increased, the overall air/pulverized

mixture is allowed less time to mix and combust fully. In this mode of operation, unburned coal particles are expected to exit the combustor chamber.

Figure 30. Base Velocity

Figure 31. Increased Velocity Level
1

Figure 32. Increased Velocity Level
2

Figure 33. Increased Velocity Level
3

Figure 34. CH Intensity

Figure 35. OH Intensity

Figure 36. CH/OH Ratio

Figure 37. Light Intensity at 410 nm

Swirl variation

This test examined the impact of varying the swirl index on the pulverized coal/air flame. The swirl index is an arbitrary unit that quantifies the injection angle of the secondary air with respect to the axial direction of the flame. This injection angle is intended to enhance the mixing of the secondary combustion air to the primary coal/air stream. The mixing of the secondary air stream to the primary coal/air stream starts inside the burner mouth and continues in the combustion chamber. As Figure 38, Figure 39, Figure 40, and Figure 41 show, increasing the swirl index promotes more rapid mixing of the coal and the oxidant which results in more intense combustion closer to the mixing nozzle.

Therefore, the flame front travels closer to the root of the flame even enters the burner mixing nozzle at maximum swirl. Both the OH and CH peak intensities increase as the swirl

index increases (Figure 42 and Figure 43). This is expected since the increased coal oxidant mixing promotes more complete combustion and subsequent radical emission.

Figure 38, Swirl 6

Figure 39, Swirl 7

Figure 40, Swirl 10

Figure 41, Swirl 12

Figure 42. CH Intensity

Figure 43. OH Intensity

Figure 44. CH/OH Ratio

Figure 45. Light Intensity at 410 nm

Conclusions

The results to date have proven that OH* and CH* excited radical emissions in coal/air flames can be detected and quantified. The information in Figure 42, Figure 43, Figure 44, and Figure 45 shows that the maximum emission intensities of OH*, CH*, and black body (char combustion) occur at different axial positions along the flame length. An illustration of this idea is shown in Figure 46. Therefore, the rates of exited CH* and OH* are distinct at different stages of the coal combustion. It is reasonable to believe that the characteristic stages, or zones, where devolatilization, char heating and burning occur can be identified and possibly quantified by correlating the CH* and OH* intensity information at given flame zones.

Figure 46. OH and CH intensity distributions

The GTI gasifier sensor is capable of detecting the affects on coal flames caused by swirl variation, injection velocity variation and oxidizer to coal ratio. Based on the results of Task 3, the test matrix for future testing on the CANMET Pressurized Entrain Flow gasifier has been modified and simplified accordingly. We believe that the probability of the successful testing and further development of the sensor technology has increased substantially.

**Appendix D US 7,907,272 B2, Fiber Optic Spectroscopic Digital Imaging
Sensor and Method for Flame Properties Monitoring**

(10) **Patent No.:** US 7,907,272 B2
(45) **Date of Patent:** Mar. 15, 2011

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Primary Examiner — Kara E Geisel
(74) Attorney, Agent, or Firm — Mark E. Fejer

(57) **ABSTRACT**

A system for real-time monitoring of flame properties in combustors and gasifiers which includes an imaging fiber optic bundle having a light receiving end and a light output end and a spectroscopic imaging system operably connected with the light output end of the imaging fiber optic bundle. Focusing of the light received by the light receiving end of the imaging fiber optic bundle by a wall disposed between the light receiving end of the fiber optic bundle and a light source, which wall forms a pinhole opening aligned with the light receiving end.

11 Claims, 10 Drawing Sheets

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(58) **Field of Classification Search** 356/300;
250/554; 359/507, 509

See application file for complete search history.

Fig. 1

Fig. 2

Fig. 3

Fig. 5

Wavelength, nm

Fig. 6

Fig. 7(a) **Fig. 7(b)**

Fig. 8

Fig. 9(a) Fig. 9(b) Fig. 9(c)

Fig. 10

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FIBER OPTIC SPECTROSCOPIC DIGITAL IMAGING SENSOR AND METHOD FOR FLAME PROPERTIES MONITORING

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Contract No. DE-FC26-02NT41585 awarded by the U.S. Department of Energy.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method and apparatus for monitoring the properties of flames in high pressure combustors and gasifiers in real time. More particularly, this invention relates to a sensor for real-time monitoring of flame properties using fiber optic spectroscopic digital imaging. Although intended for use in connection with pressurized combustors and gasifiers, the method and apparatus of this invention may be employed in any combustion apparatus in which slagging occurs or in which the environment of the combustion process is particle- and/or particulate-laden, i.e. a "dirty" or "dusty" environment, including processes at about atmospheric pressure.

2. Description of Related Art

Real-time monitoring of flame properties in high pressure combustors and gasifiers is increasingly important for providing stability, control, and optimization of combustion processes. Present control methods are mostly limited to the measurement of global system parameters such as output product compositions and emission levels or to the measurement of parameters which provide only limited information regarding the overall processes. Measurements performed inside the flame zone using thermocouples or optical pyrometers generally provide only point or line-of-sight information that is insufficient for characterizing the overall combustor performance. See, for example, U.S. Pat. No. 4,400,097 to Koschnitzke et al. which teaches a system for measuring temperatures in a high pressure reactor using an optical pyrometer which is in optical communication with a measuring duct which may be disposed in the reactor wall and is in optical communication with the reactor interior.

The use of fiber optics in a flame analyzer for analyzing one or more properties of a flame is known. U.S. Pat. No. 4,644,173 to Jeffers teaches a flame analyzer comprising a fiber optic array having a plurality of optic fibers, each of which has a light receiving end lying in a line and facing a flame. Each fiber of the array collects light from a specific location in the flame along a line extending parallel to the flame and burner axis or extending perpendicular to the flame axis. The light received by the fiber optic array is provided as a sheet of light to a monochromator which spreads the light into its component wavelengths. A pair of spaced apart arrays of light detectors is then utilized to measure the light at two discrete wavelengths. The detection produces signals that can be analyzed to generate temperature and particles distribution values for the flame across its length or width.

U.S. Pat. No. 5,828,797 to Minnott et al. teaches a fiber optic linked flame sensor for continuous optical monitoring of the combustion process within the combustion chamber of a gas turbine engine, which sensor includes a high temperature optical probe, a fiber optic cable, and an electro-optics module. The high temperature probe is mounted on the engine skin and sighted in a manner so as to view the combustion process taking place at its origin just aft of the fuel

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nozzle. It will be appreciated that the view of this probe is limited to a very small portion of the combustion process.

High pressure combustion and gasification processes would benefit enormously from novel non-intrusive imaging monitoring sensors that provide spatially-resolved information on flame properties. However, such processes present several challenges to measurements inside the combustor or gasification reactor vessels. For example, to effect temperature measurements within gasification reactor vessels using conventional means requires the insertion of a temperature probe into the gasifier. However, slag on the walls of the gasifier must be traversed by the probe if measurements are to be made within the interior of the gasifier. In addition, reliability of the measurements is difficult to obtain due to the harsh environment inside the gasifier in the form of dust particles, etc., which tend to obscure the temperature measuring device such that measurements therein may not be obtainable at all or, if obtainable, may be distorted. U.S. Pat. No. 5,372,618 to Andrus, Jr. teaches a temperature measuring device which includes a slag shield mounted on the gasifier so that a portion of the slag shield extends into the gasifier through an opening with which the gasifier is provided for this purpose, and a temperature measuring instrument in the form of a radiation thermometer or optical pyrometer mounted in supported relation within the slag shield so that line-of-sight exists from the temperature measuring instrument into the interior of the gasifier at a point of interest for temperature measurement. The temperature measuring instrument is provided with cooling means for cooling at least the portion of the slag shield extending into the interior of the gasifier and is provided with purge gas means for supplying a flow of purge gas in the area around the temperature measuring instrument to purge particulate matter therefrom and, thus, ensure that the line-of-sight between the temperature measuring instrument and the interior of the gasifier remains unobscured.

SUMMARY OF THE INVENTION

It is one object of this invention to provide a system for flame properties monitoring in a combustor or gasifier which is capable of characterizing the overall combustor or gasifier performance.

It is another object of this invention to provide a system for flame properties monitoring in a combustor or gasifier which is non-intrusive with respect to the interior of the combustor or gasifier.

It is still a further object of this invention to provide a non-intrusive imaging monitoring sensor that provides spatially-resolved information on flame properties.

These and other objects of this invention are addressed by a sensor comprising an imaging fiber optic bundle coupled with a spectroscopic imaging system employing an imaging monochromator and intensified CCD camera. In accordance with one embodiment of this invention, the input plane of the imaging fiber optic bundle is positioned in the refractory of a combustor or gasifier reactor vessel wall in close proximity of the inner reactor cavity of the combustor or gasifier reactor vessel, thereby providing a wide observation angle. The light emitted from various locations within the combustor or reactor vessel is collected by the fiber optic bundle and transmitted as an image to the spectroscopic imaging system where the emitted light can be analyzed to provide spectrally-resolved light intensities in the ultra-violet and visible region. Unique to the system of this invention is the use of a pinhole-sized observation port through which the light from within the combustor or gasifier passes to be collected by the fiber optic bundle. Use of the pinhole-sized observation port or opening

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provides a means for focusing the flame light onto the fiber optic bundle entrance, thereby obviating the placement of a lens or any other optics between the fiber optic bundle and the flame light. In addition, when using a purging gas, the pinhole-sized opening produces a high velocity low mass flow of purging gas so as to minimize the impact of the purging gas on the combustion or gasification process as well as limit any effects that the purging gas may have on the measurement process. The system further comprises a secondary purging arrangement providing tangential purging with a preheated gas so as to minimize cooling effects and, as a result, frozen slag deposition on the sensor components and refractory.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of this invention will be better understood from the following detailed description taken in conjunction with the drawings, wherein:

FIG. 1 is a schematic diagram of a sensor in accordance with one embodiment of this invention;

FIG. 2 is a schematic diagram of a sensor in accordance with one embodiment of this invention showing purging gas flow;

FIG. 3 is a schematic diagram of a sensor in accordance with one embodiment of this invention disposed within a burner nozzle;

FIG. 4 is a lateral cross-sectional view of a sensor probe and housing extending into the refractory wall of a gasifier;

FIG. 5 is a diagram showing the key diagnostic features of a gasifier flame for a natural gas flame used for preheating;

FIG. 6 is a diagram showing the relative intensities of blackbody radiation in the range of about 520 nm to about 570 nm for a natural gas flame and two coal flames;

FIGS. 7(a) and 7(b) are diagrams showing the spectra for CH* radicals in natural gas (a) and coal (b) flames;

FIG. 8 is a diagram showing the variation in OH* radical intensity as a function of oxygen/coal and steam/coal ratios;

FIGS. 9(a), 9(b), and 9(c) are diagrams showing the structure of sodium lines in a natural gas preheating flame (a) and coal flames with $O_2/C=0.85$ (b), and $H_2O/C=0.3$ (c); and

FIG. 10 is a diagram showing the relative intensity of Na lines with a steam-to-coal ratio for $O_2/C=0.85$.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

FIG. 1 is a schematic representation of the salient features of the system of this invention. As shown therein, the system comprises a wall 10 having a pinhole opening 11. Imaging fiber optic bundle 12 having a light receiving end 15 and a light output end 16 is disposed on one side of wall 10 with the flame 13 to be monitored disposed on the opposite side of wall 10. Light receiving end 15 of the imaging fiber optic bundle is aligned with pinhole opening 11. Pinhole opening 11 acts to focus the flame image received by the light receiving end of the fiber optic bundle. As used herein, the term "pinhole" refers to openings having a diameter in the range of about 1 μ m to about 1 mm. In accordance with one particularly preferred embodiment of this invention, pinhole opening 11 has a diameter in the range of about 10 μ m to about 100 μ m. Unexpectedly, the use of a pinhole opening obviates the need for focusing lenses, protective windows, or any other object intervening between the light receiving end of the imaging fiber optic bundle and the flame being monitored which could impact the measurement process.

FIG. 2 shows a sensor in accordance with one embodiment of this invention for monitoring a gasifier flame 13 sustained

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in a high pressure vessel with high temperature refractory walls 33. The light receiving end 15 of imaging fiber optic bundle 12 is positioned within refractory wall 33 and is aligned with pinhole opening 11 formed by wall 10. Pinhole opening 11 enables a wide field of view as indicated by view lines 34 and 35 encompassing an extended flame area. In accordance with one embodiment of this invention, wall 10 is an orifice plate having a pinhole opening.

As shown in FIG. 2, in accordance with one embodiment of this invention, imaging fiber optic bundle 12 is disposed within a pressurized enclosure 30. Operably connected with light output end 16 of imaging fiber optic bundle 12 is a spectroscopic imaging system 14 for analyzing the image transmitted by the bundle. In accordance with one embodiment of this invention, spectroscopic imaging system 14 comprises an imaging monochromator and high-sensitivity digital camera that can be positioned inside or outside of the pressurized enclosure. The pressurized enclosure and fiber optic bundle in accordance with one embodiment of this invention are cooled by a circulating water system, such as a water jacket having a circulating water inlet 32 and a circulating water outlet 36. The interior of enclosure 30 is continuously purged by means of a purging gas introduced into the enclosure through purge gas inlet 31. The purge gas, which may be any suitable gas, but is preferably air, is used to prevent contamination of the light receiving end 15 of imaging fiber optic bundle 12 with solid and liquid particles entrained in the swirling gases inside the combustor or gasifier. As shown in FIG. 2, the flow of purge gas is preferably parallel to the direction of the fiber optic bundle. In accordance with one preferred embodiment, the purge gas is preheated, thereby enabling heating of the fiber optic bundle and reducing the impact that cooling of the fiber optic bundle may have on the overall light collection and transmission process.

FIG. 3 shows a schematic diagram of one embodiment of this invention in which an imaging optical fiber 40 is disposed within the innermost flow conduit 42 of a coaxially fired burner 39. As shown in FIG. 3, the burner 39 comprises an outer tube or nozzle 41, a coaxially disposed inner tube 43 disposed within the outer tube, forming a first annular region between the outer tube and the inner tube, and a coaxially disposed optical fiber conduit 42 disposed within inner tube 43, forming a second annular region between the inner tube and the optical fiber conduit. The first and second annular regions enable flow of the reactants, fuel and oxidant, as indicated by arrows 44, 45, 48, and 49, into a combustion chamber defined by wall 33 resulting in the formation of flame 13. To provide for cooling and/or purging of the region within innermost flow conduit 42, a purge gas, such as oxygen, flows through the conduit as indicated by arrows 46, 47. By virtue of this arrangement, the light receiving end of the imaging optical fiber 40 is in close proximity to the flame, thereby reducing problems associated with the presence of particles in the combustor or gasifier. In addition, this arrangement enables observation of the symmetry of the flame.

The sensor in accordance with one embodiment of this invention as shown in FIG. 4 comprises an imaging fiber optic bundle 50 having a light receiving end 51 disposed within a water-cooled jacket 52 having water inlet 53 and water outlet 54 (collectively a water-cooled probe). The water-cooled jacket forms seals 61 and 62, thereby enclosing an annular channel 63 for the flow of water. Also as shown, the light receiving end 55 of the water-cooled probe is disposed within a protective sheath 56 shown extending into an opening 57 formed by outer wall 58 and refractory wall 59 of a gasification reactor vessel. Protective sheath 56 is sized to provide an

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annular space 65 between the inner surface of the sheath and the outer surface of the water-cooled jacket. The portion of the probe external to the outer wall 58 is disposed within a housing 60 having a purge gas inlet 64 in fluid communication with annular space 65 through which purge gas flows toward the light receiving end 51 of the imaging fiber optic bundle 50 during operation of the sensor. Protective sheath 56 forms a tangential purging gas channel 66 having a tangential purging gas inlet 67 through which additional purging gas flows toward the light receiving end of the imaging fiber optic bundle to provide swirl to the purging gas at the light receiving end of the bundle. Housing 60 is provided with a high pressure feed through 68 through which the portion of the fiber optic bundle distal from the light receiving end is passed out of the housing for connection to the spectroscopic imaging system, which is external to the housing.

Analysis of spectral data for evaluation of the variations of spectra with modifications of process parameters (pressure, coal velocity, steam flow, coal-to-oxygen ratio) may be performed using key spectral features of the flame. The key diagnostic features of a gasifier flame are shown in FIG. 5 for the case of a natural gas flame used for preheating. The emission band of OH* radical is positioned at ~310 nm. The CH* radical band is close to 430 nm. Two linear spectra of potassium and sodium (Na) are observed at 410 nm and 590 nm, respectively. The blackbody radiation provides a strong background with intensity rapidly increasing with increases in wavelength. In the case of a natural gas flame, the blackbody radiation is provided by the heated refractory of the gasifier walls. In coal gasification, the main source of blackbody radiation is heated coal particulates and the relative intensity of blackbody radiation may be employed for determining the temperature of the coal flame. A coal flame is also a strong blackbody radiator as can be observed from the relative intensities of blackbody radiation in the range of wavelengths from 520 to 570 nm for a natural gas flame and two coal flames with O₂/C ratios of 0.9 and 0.95 as shown in FIG. 6. As shown in FIG. 6, the coal flame demonstrates much steeper slopes of blackbody curves, which correspond to the higher flame temperatures.

Evaluation of the temperatures of a coal flame may be effected in accordance with the following procedure. The blackbody radiation emitted by the refractory may be used as a calibration source with a known blackbody temperature ~1350° K. The spectral sensitivity of the system of this invention may be found as:

$$R(\lambda) = \text{Refractory Signal}(\lambda) / E(\lambda, T_{\text{ref}})$$

where $E(\lambda, T)$ is the spectral intensity of the blackbody for corresponding refractory wall temperatures.

The spectral intensity of blackbody radiation $F(\lambda)$ from the flame may be theoretically found as:

$$F(\lambda) = R(\lambda) * E(\lambda, TF)$$

where $E(\lambda, T)$ is the spectral intensity of the blackbody defined by Planck's law. The best fit for the $F(\lambda)$ distribution is used to determine temperature of the coal flame. The emissivity of the coal flame is assumed to be 1. The obtained flame temperatures are equal to 1610° K and 1740° K for the tested O₂/C ratios of 0.9 and 0.95, respectively. The accuracy of the measurements was determined to be about 50° K.

The spectral features of CH* radicals are strong in natural gas flames due to the presence of hydrocarbon bonds. In coal flames, CH* spectral emissions are almost indistinguishable due to the relatively low hydrogen content and strong background blackbody radiation as shown in FIGS. 7(a) and 7(b).

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However, due to intensities comparable with the noise level, these features were not employed in the analysis of the results.

Analysis of the spectral data for various firing conditions reveals that OH* intensities represent a strong indicator of oxygen/coal and steam/coal ratios. These results are presented in FIG. 6 for H₂O/C ratios of 0.2 and 0.3. As clearly shown therein, OH* intensity is higher for H₂O/C ratios of 0.2 than 0.3, thereby suggesting that OH* intensity is reduced with increases in steam content. Similarly, the OH* signal increases with increases of oxygen content for constant steam loads. As shown in FIG. 8, the OH* signal increased from about 60 a.u. to about 140 a.u. with an increase of O₂/C ratio from 0.85 to 1 for a H₂O/C ratio of 0.3. At the same time, for a H₂O/C ratio of 0.2, the OH* signal increased from 200 a.u. to 660 a.u. in the same interval of O₂/C ratios. This suggests that the OH* intensity may be a good indicator of variations in oxygen and steam contents. These data also agree well with existing kinetic models of OH* excitation in flames. The amount of OH* typically increases with oxygen enrichment while steam addition leads to increases in the non-radiative quenching rate of excited OH* in collision with water molecules.

FIGS. 9(a), 9(b) and 9(c) show that sodium lines positioned at ~590 nm may represent an excellent feature for the diagnostic analysis of coal flames due to high relative intensity and clear separation from the background. It can be clearly observed that the structure of the sodium doublet changes significantly with the transition from natural gas flame to coal flames and with variations in coal flame parameters. In natural gas flames, (FIG. 9(a)) the lines are completely separated and the line at lower wavelengths has an essentially higher intensity. In contrast thereto, the lines are partially overlapping in coal flames (FIGS. 9(b) and 9(c)). The separation pattern varies as well as the intensity ratio between the lines and the intensity ratio of line to the background. All of these features potentially may be used for diagnosis of flame parameters. For example, the ratio of Na line intensity to the intensity of the background strongly depends on steam-to-coal ratio.

FIG. 10 shows that the relative intensity of the sodium line drops rapidly with increases in the steam-to-coal ratio. When the steam-to-coal ratio is increased from 0.2 to 0.3, the relative intensity of the sodium line drops from ~5.4 to ~2. This shows about a 3-fold variation with a variation in H₂O/C ratio of 50%.

The method for real-time monitoring of flame properties in accordance with one embodiment of this invention comprises collecting light emitted by the flame of interest within the combustor or gasifier using an imaging fiber optic bundle and transmitting the light as an image through the imaging fiber optic bundle to a spectroscopic imaging system in which a selected portion of the image is transformed into an image of spectrally-resolved light intensities represented as a 3-dimensional array comprising light intensities, flame position and light wavelength. The absolute and relative intensities and shapes of spectral lines and bands generated by OH* and CH* radicals, sodium and potassium atoms, and blackbody continuum are then analyzed from which analysis at least one flame property selected from the group consisting of oxygen/coal ratio, steam/coal ratio, temperature, carbon conversion, and sulfur oxide emissions is determined.

While in the foregoing specification this invention has been described in relation to certain preferred embodiments thereof, and many details have been set forth for purpose of illustration, it will be apparent to those skilled in the art that the invention is susceptible to additional embodiments and

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that certain of the details described herein can be varied considerably without departing from the basic principles of the invention.

We claim:

1. A system for real-time monitoring of flame properties in combustors and gasifiers comprising:
 - at least one wall enclosing a space and forming a pinhole opening;
 - an imaging fiber optic bundle having a light receiving end disposed within said space and having a light output end, said light receiving end aligned with said pinhole opening;
 - a spectroscopic imaging system operably connected with said light output end of said imaging fiber bundle; and purging means for purging said space.
2. The system of claim 1, wherein said pinhole opening has a diameter in a range of about 1 μm to about 1 mm.
3. The system of claim 2, wherein said diameter is in the range of about 10 μm to about 100 μm .
4. The system of claim 1, wherein said purge means comprises a preheated purge gas.
5. The system of claim 1, wherein said light receiving end is in direct communication with light exterior to said space.
6. A system for real-time monitoring of flame properties in combustors and gasifiers comprising:

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- an imaging fiber optic bundle having a light receiving end and a light output end;
- a spectroscopic imaging system operably connected with said light output end of said imaging fiber optic bundle; and
- focusing means for focusing light received by said light receiving end of said imaging fiber optic bundle, said focusing means comprising a wall disposed between said light receiving end and a light source, said wall forming a pinhole opening aligned with said light receiving end.
7. The system of claim 6, wherein said light receiving end of said imaging fiber optic bundle is disposed within an enclosure comprising said wall.
8. The system of claim 7 further comprising purging means for purging said enclosure.
9. The system of claim 8, wherein said purging means comprises a preheated purge gas disposed within said enclosure.
10. The system of claim 6, wherein said pinhole opening has a diameter in a range of about 1 μm to about 1 mm.
11. The system of claim 10, wherein said diameter is in a range of about 10 μm to about 100 μm .

* * * * *

**Appendix E US 8,094,301 B2, Video and Thermal Imaging System for
Monitoring Interiors of High Temperature Reaction Vessels**

US008094301B2

(12) **United States Patent**
Saveliev et al.

(10) **Patent No.:** **US 8,094,301 B2**
(45) **Date of Patent:** ***Jan. 10, 2012**

(54) **VIDEO AND THERMAL IMAGING SYSTEM
FOR MONITORING INTERIORS OF HIGH
TEMPERATURE REACTION VESSELS**

(75) Inventors: **Alexei V. Saveliev**, Chicago, IL (US);
Serguei A. Zelepouga, Hoffman Estates,
IL (US); **David M. Rue**, Chicago, IL
(US)

(73) Assignees: **Gas Technology Institute**, Des Plaines,
IL (US); **The Board of Trustees of the
University of Illinois**, Urbana, IL (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 834 days.

This patent is subject to a terminal dis-
claimer.

(21) Appl. No.: **12/180,676**

(22) Filed: **Jul. 28, 2008**

(65) **Prior Publication Data**

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Related U.S. Application Data

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filed on Dec. 12, 2007, now Pat. No. 7,907,272.

(60) Provisional application No. 61/051,159, filed on May
7, 2008.

(51) **Int. Cl.**
G01J 3/28 (2006.01)

(52) **U.S. Cl.** **356/300**; 348/276; 340/578; 250/554;
250/208.1; 385/117

(58) **Field of Classification Search** 348/276;
250/208.1, 554; 385/117; 340/578

See application file for complete search history.

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Primary Examiner — Tammy Nguyen

(74) *Attorney, Agent, or Firm* — Mark E. Fejer

(57) **ABSTRACT**

A system and method for real-time monitoring of the interior of a combustor or gasifier wherein light emitted by the interior surface of a refractory wall of the combustor or gasifier is collected using an imaging fiber optic bundle having a light receiving end and a light output end. Color information in the light is captured with primary color (RGB) filters or complementary color (GMCY) filters placed over individual pixels of color sensors disposed within a digital color camera in a BAYER mosaic layout, producing RGB signal outputs or GMCY signal outputs. The signal outputs are processed using intensity ratios of the primary color filters or the complementary color filters, producing video images and/or thermal images of the interior of the combustor or gasifier.

13 Claims, 6 Drawing Sheets

C = Cyan
Y = Yellow
M = Magenta
G = Green
R = Red
B = Blue

G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G
G	B	G	B	G	B
R	G	R	G	R	G

C	Y	C	Y
M	G	M	G
C	Y	C	Y
G	M	G	M
C	Y	C	Y
M	G	M	G
C	Y	C	Y
G	M	G	M

1st
Pixel

Fig. 1
(Prior Art)

Fig. 2(a)

Fig. 2(b)

Fig. 3

Fig. 4

Temperature, K
Fig. 5

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VIDEO AND THERMAL IMAGING SYSTEM FOR MONITORING INTERIORS OF HIGH TEMPERATURE REACTION VESSELS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Contract No. DE-FC26-02NT41585 awarded by the U.S. Department of Energy.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to thermal imaging/video surveillance systems for monitoring the interiors of high temperature reaction vessels, such as combustors, gasifiers, furnaces, and boilers. More particularly, this invention relates to thermal imaging/video surveillance systems for real-time monitoring of the interiors of high temperature reaction vessels using fiber optic imaging and digital color CCD (charge coupled device) and CMOS (complementary metal oxide semiconductor) sensors. Real-time monitoring is highly desirable for improved stability, control, and optimization of combustion and gasification processes.

Presently available control methods are generally limited to the use of discrete temperature measurements and to monitoring of global system measurements performed using refractory embedded thermocouples or optical pyrometers. Such methods provide only point measurements that are often insufficient to assess temperature distribution over the entire refractory surface of the high temperature reaction vessel or to evaluate process quality. See, for example, U.S. Pat. No. 4,400,097 to Koschnitzke et al. which teaches a system for measuring temperatures in a high pressure reactor using an optical pyrometer which is in optical communication with a measuring duct which may be disposed in the reactor wall and is in optical communication with the reactor interior.

Applications of commercially available thermal imaging and pyrometer systems have been limited by a number of factors including the high cost of the systems and the inability to maintain reliable optical access to harsh, combustion/gasification environments. Thus, it is apparent that high pressure combustion and gasification processes would benefit substantially from non-intrusive imaging monitoring sensors that provide real-time monitoring of the process vessel interior. However, such processes present several challenges to measurements inside the combustor or gasification reactor vessels. For example, to effect temperature measurements within gasification reactor vessels using conventional means requires the insertion of a temperature probe into the gasifier. However, slag on the walls of the gasifier must be traversed by the probe if measurements are to be made within the interior of the gasifier. In addition, reliability of the measurements is difficult to obtain due to the harsh environment inside the gasifier in the form of dust particles, etc., which tend to obscure the temperature measuring device such that measurements therein may not be obtainable at all or, if obtainable, may be distorted. U.S. Pat. No. 5,372,618 to Andrus, Jr. teaches a temperature measuring device which includes a slag shield mounted on the gasifier so that a portion of the slag shield extends into the gasifier through an opening with which the gasifier is provided for this purpose, and which includes a temperature measuring instrument in the form of a radiation thermometer or optical pyrometer mounted in supported relation within the slag shield so that line-of-sight exists from the temperature measuring instrument into the interior of the gasifier at a point of interest for temperature measurement.

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The temperature measuring instrument is provided with cooling means for cooling at least the portion of the slag shield extending into the interior of the gasifier and is provided with purge gas means for supplying a flow of purge gas in the area around the temperature measuring instrument to purge particulate matter therefrom and, thus, ensure that the line-of-sight between the temperature measuring instrument and the interior of the gasifier remains unobscured.

SUMMARY OF THE INVENTION

It is one object of this invention to provide a low cost imaging system combining video and thermal imaging capabilities to monitor in real time the interior of high temperature reaction vessels.

It is another object of this invention to provide a system for significantly improving the quality of combustion control in high temperature reaction vessels by providing non-contact field temperature measurements with sufficient accuracy and reliability.

These and other objects of this invention are addressed by an imaging system for real-time monitoring of the interior of a high temperature reaction vessel comprising an imaging fiber optic bundle having a light receiving end and a light output end, a digital color camera comprising CCD or CMOS sensors and having a light receiving inlet in light transmission communication with the light output end of the imaging fiber optic bundle and comprising primary color, i.e. red, green, blue (RGB), or complimentary color, i.e. green, magenta, cyan, yellow (GMCY), filters placed over individual pixels of the sensors within the digital color camera in a BAYER mosaic layout, focusing means for focusing light to be received by the light receiving end of the imaging fiber optic bundle, which focusing means comprises a wall disposed between the light receiving end and a light source forming a pinhole opening aligned with the light receiving end, and processing means for processing the light received by the individual pixels to produce at least one of a video image and a thermal image of the interior of the high temperature reaction vessel.

These and other objects of this invention are further addressed by a method for real-time monitoring of the interior of a combustor or gasifier in which light emitted by an interior surface of a refractory wall of the combustor or gasifier is collected using an imaging fiber optic bundle having a light receiving end and a light output end. The color information in the collected light, which is output from the light output end of the imaging fiber optic bundle, is captured using primary color (RGB) filters or complimentary color (GMCY) filters placed over individual pixels of color sensors arranged in a BAYER mosaic layout disposed within a digital color camera, producing RGB or GMCY signal outputs. The signal outputs are then processed using intensity ratios of the primary color filters or the complimentary color filters, producing video images and/or thermal images of the interior of the combustor or gasifier which may be displayed on a suitable display, such as a video monitor.

The system of this invention provides substantial benefits to high pressure and temperature combustion and gasification processes by virtue of the novel non-intrusive reliable video surveillance/thermal imaging features of the system that provide spatially-resolved information on the combustion/gasification apparatus interior.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of this invention will be better understood from the following detailed description taken in conjunction with the drawings wherein:

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FIG. 1 is a diagram providing representations of the Bayer mosaic RGB and GMCY patterns;

FIG. 2(a) is a diagram showing exemplary spectral sensitivity functions for RGB filters and FIG. 2(b) is a diagram showing exemplary spectral sensitivity functions for GMCY filters;

FIG. 3 is a diagram showing I_G/I_R , I_B/I_R , I_G/I_B ratios as functions of temperature for illumination with an ideal black body source;

FIG. 4 is a diagram of a system for monitoring the temperature of gasification and combustion reactor vessel refractory walls in accordance with one embodiment of this invention; and

FIG. 5 is a diagram showing an exemplary experimental temperature calibration for use in accordance with one embodiment of this invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

The video and thermal imaging system of this invention utilizes color digital signals and calibration functions for temperature recognition inside high temperature reaction vessels. The thermal imaging system of this invention comprises a digital CCD or CMOS color camera. The color sensors employed in these cameras possess high dynamic range, sensitivity, and fast imaging capabilities. The color sensors capture the color information via so-called primary color (red, green, blue) or complimentary color (green, magenta, cyan, yellow) filters placed over the individual pixels in a BAYER mosaic layout as shown in FIG. 1. For many cameras, the processing of color BAYER readouts can be performed outside the camera using a digital data processor or personal computer. This corresponds to the so-called raw data output mode of the camera. Because of the known and constant spectral sensitivities of various filters as shown in FIGS. 2(a) and 2(b), algorithms may be developed to convert the raw mode BAYER data outputs to the temperature data for each imaging pixel. The digitized signal of individual pixel filters in RGB or GMCY pattern are processed to infer the signal intensity ratios for each individual pixel, e.g. I_G/I_R , I_B/I_R , I_G/I_B . The camera is preliminarily calibrated using refractory material substantially identical to the refractory material in the reaction vessel. The calibration is performed over the temperature region of interest. The temperature calibration function is performed and the results stored in a refractory database of a digital processor. The temperature calibration function is a function of at least one intensity ratio but may also involve up to 3 intensity ratios for KGB patterns and up to 6 intensity ratios for GMCY patterns. The measured intensity ratios for each individual pixel are converted to temperature using the calibration functions stored in the database. The thermal image is formed based on the temperatures acquired for each individual pixel.

In this invention, the digital RGB or GMCY signals are used for performing low-cost thermal imaging using a specific processing algorithm. This algorithm reconstructs temperature T using intensity ratios for various color filters. The color recognition algorithm can be illustrated using theoretical black body intensity (Planck's law) and RGB filter sensitivities shown in FIGS. 2(a) and 2(b). Consider that black body radiation is directed to the camera sensor. The intensity of the radiation $M(\lambda, T)$ is given by Planck's formula. The

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digital intensity outputs I_R , I_G , I_B of the corresponding filters can be represented as:

$$I_R = K \int f_R(\lambda) M(\lambda, T) d\lambda$$

$$I_G = K \int f_G(\lambda) M(\lambda, T) d\lambda$$

$$I_B = K \int f_B(\lambda) M(\lambda, T) d\lambda$$

where $f(\lambda, T)$ are the spectral sensitivity functions of individual RGB filters and K is the proportionality coefficient. The intensity ratios I_G/I_R , I_B/I_R , I_G/I_B are functions of temperature only and can be used for temperature recognitions. The calculated ratios I_G/I_R , I_B/I_R , I_G/I_B are plotted as a function of temperature in FIG. 3. The spectral sensitivity functions shown in FIG. 2(a) are used. It can be clearly seen that temperature can be reconstructed with sufficient accuracy using these calculated calibration functions.

In a real imaging system illuminated by a gray body at temperature T, digital intensity outputs I_R , I_G , I_B can be represented as:

$$I_R = K \int S(\lambda) f_R(\lambda) \epsilon(\lambda, T) M(\lambda, T) d\lambda$$

$$I_G = K \int S(\lambda) f_G(\lambda) \epsilon(\lambda, T) M(\lambda, T) d\lambda$$

$$I_B = K \int S(\lambda) f_B(\lambda) \epsilon(\lambda, T) M(\lambda, T) d\lambda$$

where $\epsilon(\lambda, T)$ is a spectral emissivity of radiating material that generally depends both on temperature and wavelength and $S(\lambda)$ is a spectral transmission function of the focusing optics. However, the intensity ratios I_G/I_R , I_B/I_R , I_G/I_B remain the functions of temperature only and can be used for temperature recognitions. These intensity ratios I_G/I_R , I_B/I_R , I_G/I_B can be calibrated against high temperature radiating sources and calibration functions stored and later used for temperature recognition. Using this algorithm, the function F can be obtained from the sensor calibration performed at a high temperature range for various refractory materials and stored in the computer database. In general, it may be represented as a function of one or more intensity ratios. However, the function of only one intensity ratio can be sufficient, e.g.:

$$T = F\left(\frac{I_B}{I_R}\right)$$

FIG. 4 is a schematic representation of the salient features of the system of this invention. As shown therein, the system comprises an imaging fiber optic bundle 10 having a light receiving end 11 and a light output end 12 and a digital color camera 13 having a light receiving inlet 14 in light transmission communication with light output end 12 of imaging fiber optic bundle 10. In accordance with one embodiment of this invention, a relay lens 21 is provided to facilitate the transmission of light between the light output end 12 of the imaging fiber optic bundle 10 and the light receiving inlet 14 of the digital color camera 13. The digital color camera is provided with primary or complimentary color filters placed over individual pixels of sensors within the digital camera in a BAYER mosaic layout as shown in FIG. 1. Focusing means comprising a wall 15 disposed between light receiving end 11 and a light source, typically the interior of a gasification or combustion apparatus of interest, and forming a pinhole opening 16 aligned with light receiving end 11 of imaging fiber optic bundle 10 are provided for focusing light to be received by the imaging fiber optic bundle. Pinhole opening 16 acts to focus the light from within the high temperature reaction vessel received by the light receiving end of the fiber optic bundle.

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As used herein, the term “pinhole” refers to openings having a diameter in the range of about 1 μm to about 1 mm. In accordance with one particularly preferred embodiment of this invention, pinhole opening **16** has a diameter in the range of about 10 μm to about 100 μm . Unexpectedly, the use of a pinhole opening obviates the need for focusing lenses, protective windows, or any other object intervening between the light receiving end of the imaging fiber optic bundle and the interior of the high temperature reaction vessel being monitored which could impact the measurement process.

To protect the imaging fiber optic bundle from the harsh environment of the gasification or combustion apparatus, the bundle is disposed within a housing **17** having a purge gas inlet **18** through which a purge gas, such as nitrogen, is introduced into the housing. In accordance with one embodiment of this invention, a water cooled jacket **19** is disposed around housing **17** for cooling.

As previously indicated, operation of the system of this invention for monitoring the temperature of gasification/combustion apparatus refractory walls requires calibration of the digital color camera using refractory material substantially identical to the refractory material in the gasification/combustion apparatus. The results of the calibration are stored in a database in a digital processor **20** which interfaces with the digital color camera **13** through communication means by which the digital RGB or GMCY signal output of the digital camera is transmitted into the digital processor as shown in FIG. **4**. The digital video or thermal imaging output of the digital processor is transmitted into a suitable display **25**, such as a video monitor, with which it is operably connected.

As shown in FIG. **4**, during operation of the system of this invention for monitoring the temperature of gasification or combustion apparatus refractory walls, the imaging fiber optic bundle is inserted through an opening in one of the refractory walls of the gasification or combustion apparatus. Light emitted by the refractory walls is focused on the imaging bundle entrance with the focusing pinhole. The focusing element is capable of collecting light at a wide viewing angle covering an extended area. The fiber optic bundle is cooled by circulating water. The purging air (nitrogen) flow is used to prevent contamination of the transmitting and collecting optic with solid and liquid particles entrained in the swirling gases inside the gasifier/combustion system. The image is transmitted through the fiber optic bundle to the camera where it is digitized and recorded using red, green, and blue components. Further red, blue, and green intensities are processed to form intensity ratios. The temperature for each pixel is obtained using calibration functions (FIG. **5**) that have been preliminarily recorded for the refractory material of the vessel. As a result, the temperature distribution over the full field of view is obtained and represented as a computer image.

As an example, the calibration function of a CCD digital color camera for alumina refractory material (FIG. **5**) allows fast temperature recognition in the range from 1100 to 1500 K using simple linear temperature dependence on I_B/I_R ratio. As a result, video and thermal imaging can be performed simultaneously for a real time process control.

While in the foregoing specification this invention has been described in relation to certain preferred embodiments thereof; and many details have been set forth for the purpose of illustration, it will be apparent to those skilled in the art that the invention is susceptible to additional embodiments and that certain of the details described herein can be varied considerably without departing from the basic principles of this invention.

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We claim:

1. An imaging system for real-time monitoring of an interior of a high temperature reaction vessel comprising:
 - an imaging fiber optic bundle having a light receiving end and a light output end;
 - a digital color camera comprising one of CCD and CMOS sensors and having a light receiving inlet in light transmission communication with said light output end and comprising one of primary color (RGB) and complimentary color (GMCY) filters placed over individual pixels of said sensors within said digital color camera in a BAYER mosaic layout;
 - focusing means for focusing light to be received by said light receiving end of said imaging fiber optic bundle, said focusing means comprising a wall disposed between said light receiving end and a light source, said wall forming a pinhole opening aligned with said light receiving end; and
 - processing means for processing said light received by said individual pixels to produce at least one of a video image and a thermal image of said interior of said high temperature reaction vessel.
2. The system of claim **1** further comprising viewing means for viewing said at least one of said video image and said thermal image operably connected with said processing means.
3. The system of claim **1** further comprising a relay lens disposed between said light outlet end of said imaging fiber optic bundle and said light receiving inlet of said digital color camera.
4. The system of claim **1** further comprising a housing disposed around said imaging fiber optic bundle, wherein said wall comprises one portion of said housing.
5. The system of claim **4** further comprising purge means for purging an inside of said housing.
6. The system of claim **4** further comprising cooling means for cooling an inside of said housing.
7. The system of claim **6**, wherein said cooling means comprises a cooling jacket disposed on an exterior surface of said housing.
8. The system of claim **4**, wherein said light receiving end of said imaging fiber optic bundle is in direct communication with light exterior to said housing.
9. The system of claim **1**, wherein said pinhole opening has a diameter in a range of about 1 μm to about 100 μm .
10. The system of claim **9**, wherein said diameter is in a range of about 10 μm to about 100 μm .
11. A method for real-time monitoring of an interior of a combustor or gasifier comprising the steps of:
 - collecting light emitted by an interior surface of a refractory wall of said combustor or gasifier using an imaging fiber optic bundle having a light receiving end and a light output end;
 - capturing color information in said light from said light output end with one of primary color (RGB) filters and complimentary color (GMCY) filters placed over individual pixels of color sensors disposed within a digital color camera in a BAYER mosaic layout, producing one of RGB signal outputs and GMCY signal outputs; and
 - processing said signal outputs using intensity ratios of said one of said primary color filters and said complimentary color filters, producing at least one of video images and thermal images of said interior of said combustor or gasifier.

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12. The method of claim **11**, wherein said imaging fiber optic bundle is disposed within a housing and said light is focused by a pinhole formed by a wall of said housing disposed between said imaging fiber optic bundle and said interior surface of said refractory wall.

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13. The method of claim **12**, wherein an inside of said housing is purged using a purge gas.

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