Real Time Flame Monitoring of Gasifier Burner and Injectors

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

Topical REPORT
(April 2003 - 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
Co-operative Agreement No. DE-FS26-02NT41585

DOE Project Manager
Jenny Tenant

October 2003

Disclaimer

Abstract

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.

Table of Contents

List of Tables

List of Figures

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.

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 burnet 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.

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.

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								
3	Bench-Scale Sensor Testing						4							
4	Burner Condition Testing									5				
5	Preparation for Gasifier Testing										6			
6	Gasifier Flame Sensor Testing											7	8	9

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

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.

Executive Summary

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.

Experimental

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).

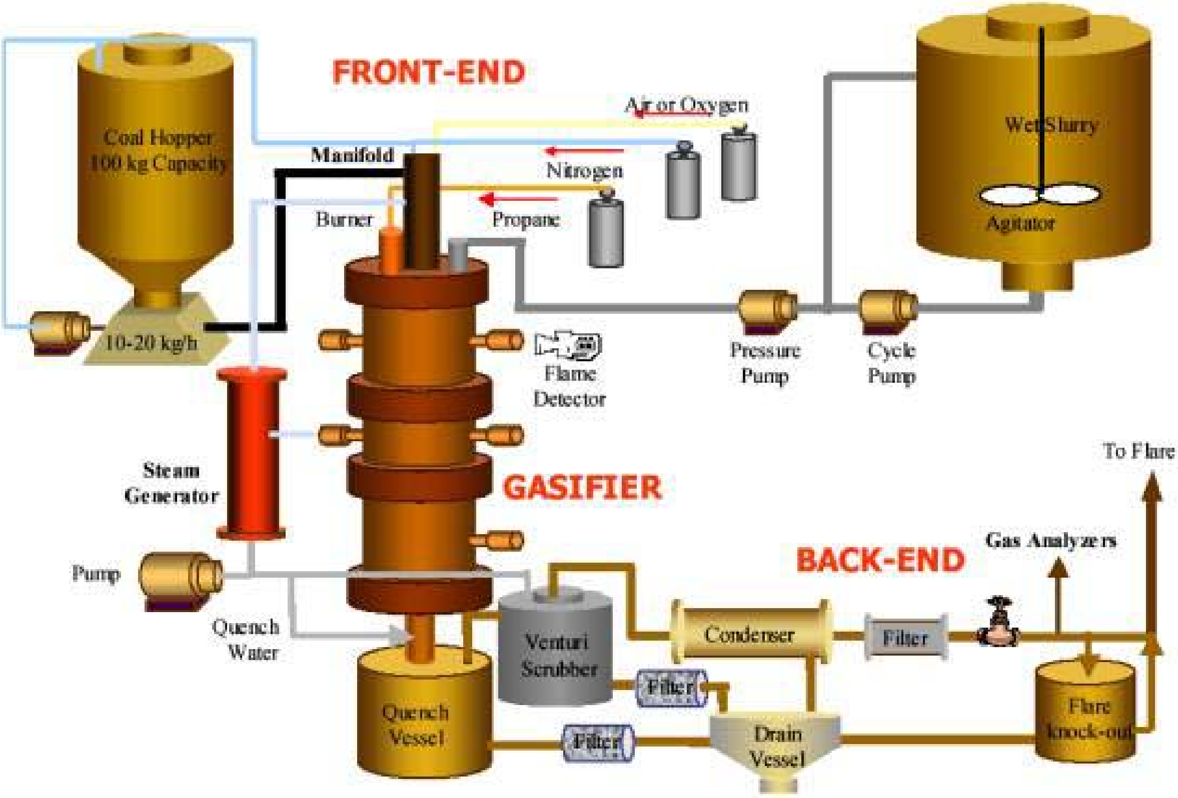


Figure 1. Entrained Flow Gasifier

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 (l400-1800°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 ensures 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 800-900ºC 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 240ºC. 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 verturi 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 verturi 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.

Results and Discussion

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 that 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.

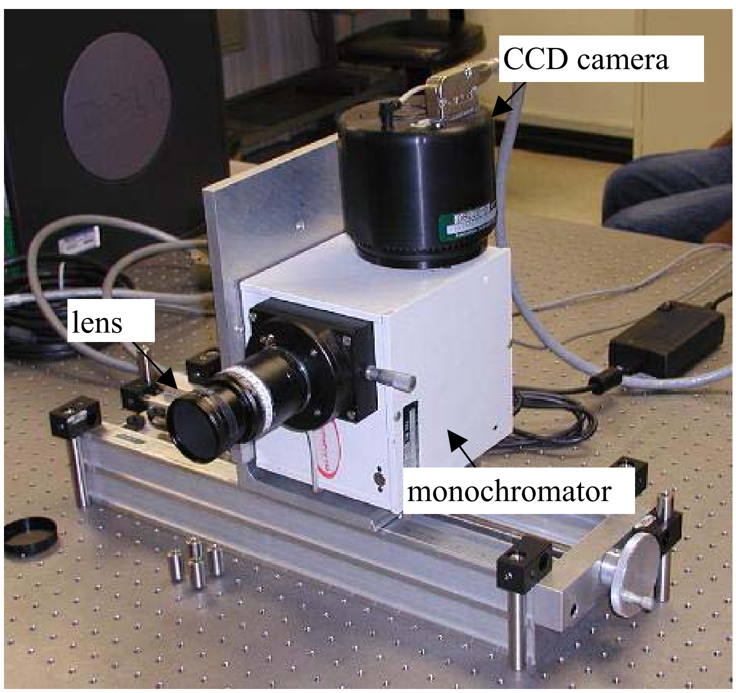


Figure 2. 1-D Optical Sensor Consisting of CCD Camera, Monochromator, and Lens.

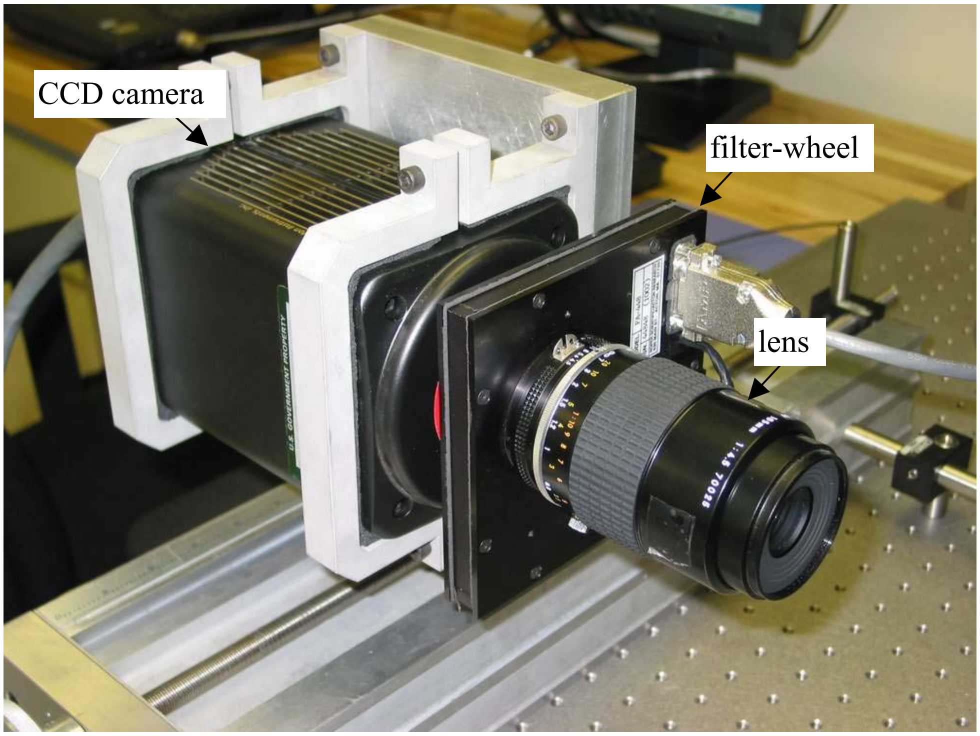


Figure 3. 2-D Optical Sensor Consisting of CCD Camera, Filter-Wheel, and Lens.

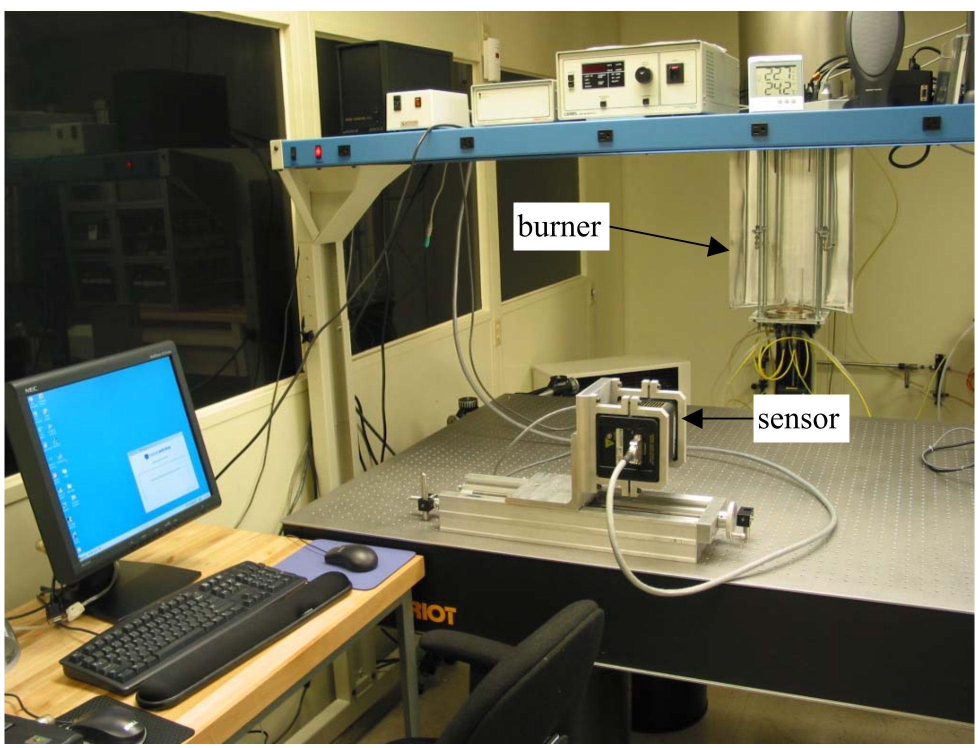


Figure 4. 2-D Optical Sensor Positioned for Data Acquisition From the Test Burner.

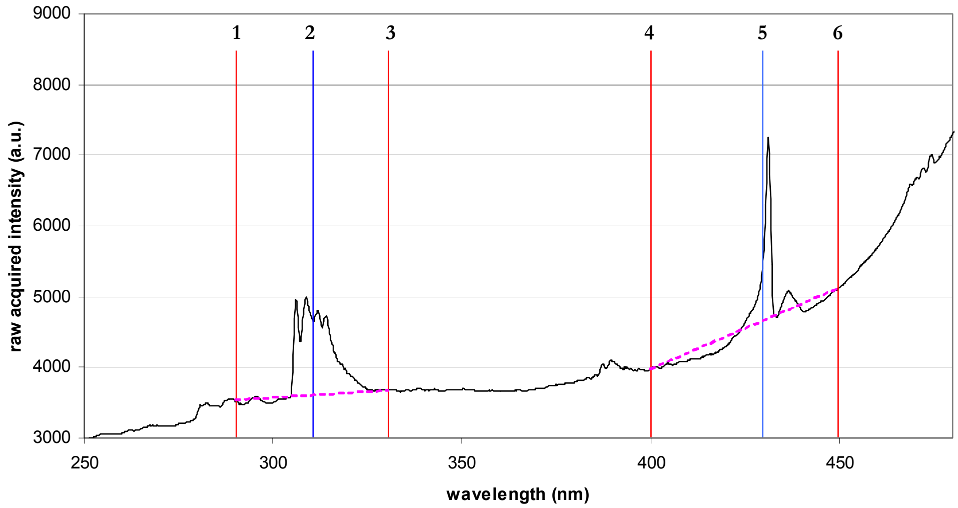
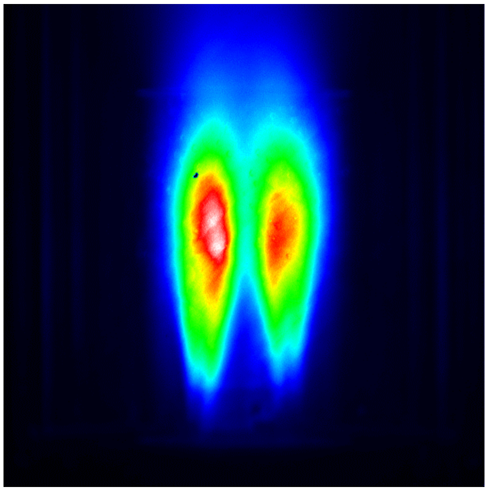


Figure 5. Natural Gas Flame Spectrum Showing the Six Filter Center Locations and the Subtracted Background Radiation (in pink).

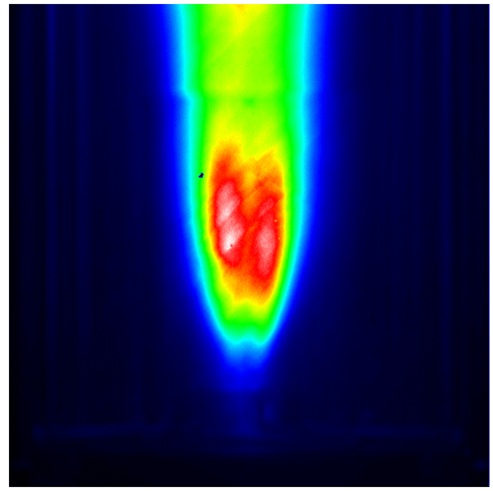
(a) 0.18in. air nozzles

(b) 0.32in. air nozzles

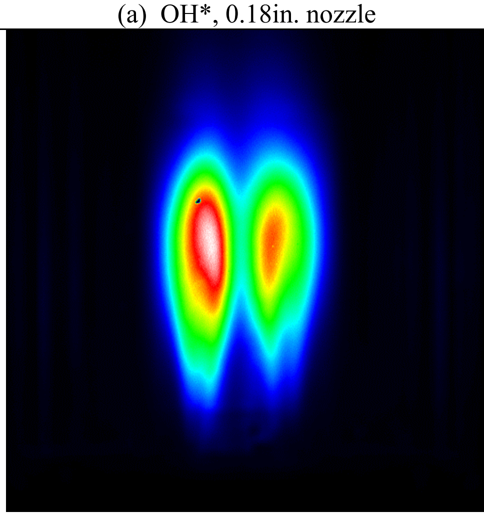
Figure 6. Flame Photographs From the Test Burner Running at 0% Excess Air.



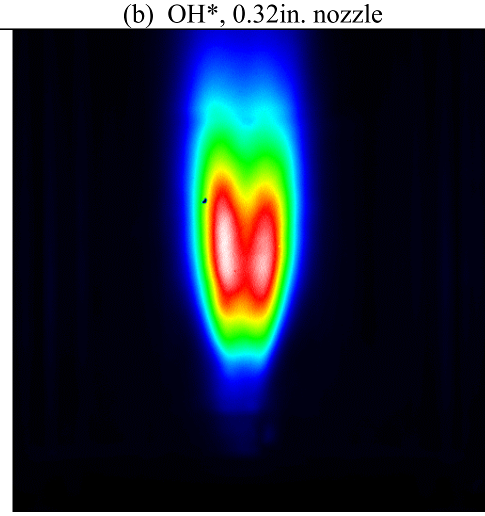
(a) OH*, 0.18in. nozzle



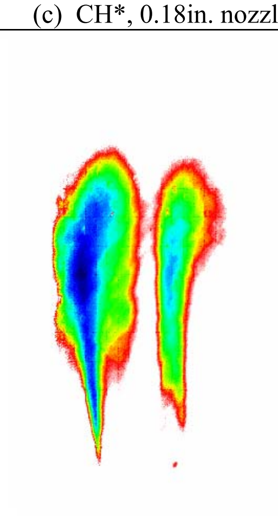
(b) OH*, 0.32in. nozzle



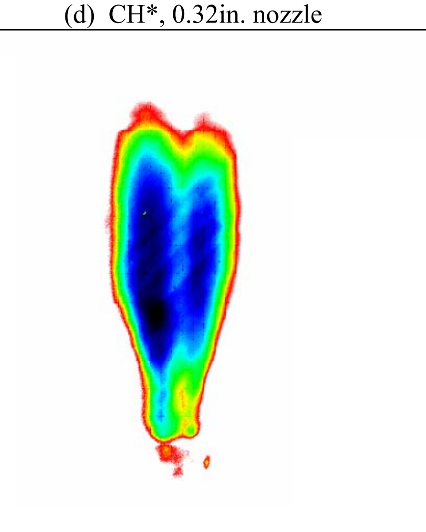
(c) CH*, 0.18in. nozzle



(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

The sensor has been demonstrated to work on natural gas flames with background radiation (soot can cause background radiation) and to distinguish different combustion regimes. The second version of the sensor is both simpler and more robust than the first version. 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. First, the sensor hardware and software will continue to be improved. The objective is to develop a real-time device with the necessary data analysis software. This device needs to work reliably and collect appropriate data and data trends to detect burner wear and changes in combustion patterns. Work will also begin on hardening the sensor for demonstration testing. This will involve assembling an enclosure for the camera and filter wheel. The enclosure is expected to be air- or 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.).