On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement

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Principal Authors: Kristie Cooper, Gary Pickrell, Anbo Wang, Zhengyu Huang

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Submitted by: Center for Photonics Technology
Bradley Department of Electrical Engineering
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061-0111

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Abstract

This report summarizes technical progress over the third six month period of the Phase II program “On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement”, funded by the Federal Energy Technology Center of the U.S. Department of Energy, and performed by the Center for Photonics Technology of the Bradley Department of Electrical and Computer Engineering at Virginia Tech.

The outcome of the first phase of this program was the selection of broadband polarimetric differential interferometry (BPDI) for further prototype instrumentation development. This approach is based on the measurement of the optical path difference (OPD) between two orthogonally polarized light beams in a single-crystal sapphire disk. The objective of this program is to bring the BPDI sensor technology, which has already been demonstrated in the laboratory, to a level where the sensor can be deployed in the harsh industrial environments and will become commercially viable.

Research efforts were focused on sensor probe design and machining, sensor electronics design, software algorithm design, sensor field installation procedures, and sensor remote data access and control. Field testing will begin in the next several weeks.

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1.0 Introduction

In the first phase of this program, five different optical temperature sensing schemes were thoroughly investigated to determine an optimal approach for high temperature measurement in coal gasification systems. Based on comparative evaluation and analysis of the experimental results, the broadband polarimetric differential interferometry (BPDI) was chosen for further prototype instrumentation development. This approach is based on the self-calibrating measurement of the optical path difference (OPD), *i.e.* phase retardation between the two orthogonally polarized light beams in a single-crystal sapphire disk, which is a function of both the temperature dependent birefringence and the temperature dependent dimensional sizes.

In the past half-year, efforts were focused on preparing for the upcoming field tests, including design of the sensors probe, accompanying electronics, and software algorithm, development of installation procedures preparation for remote data access and control.

2.0 Executive Summary

This report summarizes the technical progress over the third six month period of the Phase II program “On-Line Self-Calibrating Single Crystal Sapphire Optical Sensor Instrumentation for Accurate and Reliable Coal Gasifier Temperature Measurement”, funded by the Federal Energy Technology Center of the U.S. Department of Energy, and performed by the Center for Photonics Technology of the Bradley Department of Electrical and Computer Engineering at Virginia Tech.

During the reporting period, research efforts under the program were focused on the following.

- Design and machining of the sensor probe.

Under normal conditions, the temperature of the vessel shell is 450°F and the temperature inside the coal gasifier is estimated to be around 3000°F. The process pressure inside the coal gasifier is 450psig. Following discussion with personnel at Wabash River Energy and Conoco-Philips, the mechanical packaging design was finalized based on a pressure vessel Wabash River Energy has used in their former applications. The necessary parts were machined and assembled in preparation for field testing.

- Design of sensor electronics

The enclosure for the sensor electronics must satisfy National Electrical Code Class I, Division II, Group B requirements. The sensor data processing computer will be placed in the control room on the 3rd deck of the building, which is 520ft from the sensor mounting location on the 4th deck. Computer control and sensor data transfer will be realized through a USB extender.. The remaining electronic components were designed and assembled in a suitable enclosure.

- Software algorithm design

Several algorithms were developed and modified to extract the signal from the large background using LED on-off modulation.

- Development of field test installation procedures
- Development of remote data access capability

Remote data acquisition and sensor computer control were established in order to operate and monitor the system from Virginia Tech.

Site preparation and installation for the gasifier field test are scheduled over the next several weeks. Efforts during the coming months will focus on evaluation of the sensor prototype and analysis of the field test results.

3.0 Theory of Sensor Operation

The working principle of the broadband polarimetric differential interferometric (BPDI) sensing system is shown in Figure 3.1. The broadband light from a high power light emitting diode is injected into a multimode optical fiber and propagates through a two by two fiber coupler to the sensor head. The light is first converted into a linearly polarized collimated optical beam and travels across a free space enclosed by a high temperature ceramic tube and a single crystal sapphire tube to a single crystal sapphire disk, functioning as the sensing element. The sapphire disk is arranged such that the linear polarization is at 45° with respect to the fast and slow axes of the crystal. After passing through the sapphire disk, the two linear polarization components along the fast and slow axes experience a differential phase delay due to the sapphire birefringence. The light, containing the two different linear polarization components, is then reflected by a right angle zirconia prism and passes through the sapphire sensing element again, so the differential phase retardation is doubled. The two linear components with a differential phase delay are then combined along the polarizer direction to interfere with each other. The light is then collected by the same input optical fiber and travels back along the same fiber and through the same coupler to the optical detection end. The returned light intensity can be expressed as

$$I(\lambda) = 2kI_s(\lambda) \left(1 + \cos \left(\frac{2\pi d(T) \Delta n(T)}{\lambda} \right) \right), \quad (3-1)$$

where $I_s(\lambda)$ is the spectral power distribution which is a function of the wavelength (λ) of the broadband light source; k is a parameter describing the power loss of the optical system, and can be treated as a constant; d is the thickness of the sapphire disk; and $\Delta n = n_o - n_e$ is the birefringence of the sapphire disk. Both d and Δn are functions of the temperature T . From this equation, it can be seen that the output spectral density is a function of the light wavelength and the differential phase delay, which is a function of temperature. It is therefore possible to extract the temperature information by measuring the output optical spectrum.

Figure 3.1. Schematic of the single-crystal sapphire based optical high temperature sensor.

4.0 Sensor Probe Design and Machining

Under normal conditions, the temperature of the vessel shell is 450°F and the temperature inside the coal gasifier is estimated to be around 3000°F. The temperature profile from the vessel shell to the far-end of the refractory wall can be given by linear interpolation. The process pressure inside the coal gasifier is 450psig. During our on-site visit to Wabash River Energy, Indiana on October 27th, 2003, we evaluated three candidate nozzles for use in the field test (Figure 4.1). The cross-section view of the mounting nozzle is shown in Figure 4.2 and the dimensions are shown in Table 4-1.

Figure 4.1. Sensor nozzle mounted to the coal gasifier, top view (left) and side view (right).

Figure 4.2. Cross section of mounting nozzle.

Table 4-1. Candidate mounting nozzle characteristics.

Nozzle Characteristic	Nozzle [X1]	Nozzle [X2]	Nozzle [X5]
Size/rating, in/# {1}	4" / 300#	4" / 300#	4" / 300#
Type {2}	RFLWN	RFLWN	RFLWN
Projection, in {3}	8" [204mm]	8" [204mm]	8" [204mm]
Shell thickness, in	7 1/2" [192mm]	7 1/2" [192mm]	2 3/4" [70mm]
Refractory thickness, in	1' – 8 1/4" [517mm]	1' – 8 1/4" [517mm]	2' – 5" [741mm]
Location on Reactor	Top horiz. @ 45°	Top horiz. @ 45°	Top horiz. @ transition
Total projection from flange face	35.9" [913mm]	35.9" [913mm]	40.0" [1015mm]

Notes: {1} All flanges are industry standard, conforming to ANSI B16.5. Data provided is nominal pipe size, 4" [100mm] and 300 psig pressure class.
 {2} RFLWN = Raised face, long weld neck.
 {3} Projection = distance from vessel shell O.D. to flange face.

After discussion with Mr. Bill White, Mr. Jeff Stockton at Wabash River Energy, Indiana and Mr. Ron Herbaneck at Conoco-Philips, Texas on several mechanical packaging designs, in mid-January 2004 we finalized the design, which is based on a pressure vessel Wabash River Energy provided which was used in their former applications. The pressure vessel is composed of a bell jar with three wiring outlets and a spacer with two pairs of outlets and a valve. The picture of the original bell jar and spacer provided by Wabash River Energy is shown in Figure 4.3. Figure 11 shows a device incorporating the same bell jar and spacer during operation.

Bell jar side view

Bell jar inner-view

Bell jar wiring inlets

Spacer side-view

Spacer to bell jar mounting face

Backside of spacer to bell jar mounting face (with N₂ purge inlet and outlet)

Spacer to coal gasifier nozzle mounting face

Figure 4.3. Bell jar and spacer provided by Wabash River Energy.

Figure 4.4. The existing device with bell jar and spacer packaging.

The sapphire temperature sensor packaging design for the given vessel is shown in Figure 4.5 through Figure 4.9. Table 2 lists the components ordered or machined for the probe packaging. The valve on the spacer was first cut off and the remaining parts welded together. The welding seam was hydraulically pressurized to 750psig for 80mins to ensure the quality of the weld. After welding, the spacer was reduced to 23" long. The sapphire sensing unit was mounted at the end of a 60" long 99.8% cast single bore alumina tube from Tech Ceramics, Inc. In the design, the alumina tube is used as the optical alignment basis. A 1" thick plug formed by ceramic glue was glued to the larger sapphire tube in case the single crystal bond of the sapphire disk to the sapphire tube fails and the coal slag enters. Two sapphire tubes were bonded to the alumina tube to give a maximum length of 20" of protection from coal slag corrosion. The overlap of the two sapphire tubes is 4". At the cold end where the sapphire protection ends, the temperature is only 1700°F, where the coal slag would be in solid state, and corrosion is less likely to happen. An outer alumina tube with one-end closed was used to cover the sapphire tubes and the inner alumina tube to give extra protection against the coal slag. They were bonded with high temperature ceramic glue. The coefficient of thermal expansion (CTE) of the ceramic glue is $7.8 \times 10^{-6} / ^\circ C$. CTE of 99.8% alumina is $8.0 \times 10^{-6} / ^\circ C$. CTE of single crystal sapphire is $7.8 - 8.3 \times 10^{-6} / ^\circ C$ depending on crystal orientation. The CTE mismatch between these materials is small enough that the thermal tension created at high temperature is well below the tensile strength of the ceramic glue so the whole structure will not tear apart during testing. The inner alumina tube was then inserted into the inner stainless steel pipe and bonded using epoxy and high temperature ceramic glue at the cold and hot end to ensure bonding quality. The stainless steel pipe has a

stainless steel stud with threads that is welded to it. There is a stainless steel metal reducing coupler welded to the ID of the spacer. The inner stainless steel pipe can be screwed into the metal reducing coupler and therefore bond tight together. The cold end of the stainless steel pipe was polished into a taper so that it can be fixed into a tapered screw close to the sight glass. The tapered screw ensures that the precision of the threaded coupling of the reducing coupler need not to be very high, while it still gives support to the weight of the sensor probe

Figure 4.5. Mechanical packaging design.

Figure 4.6. Mechanical packaging design (detail in bell jar and spacer).

and keeps the alignment within tolerance. At the hot end of the inner stainless steel pipe, a metal reducing coupler was put on so that it connects with a 2" stainless steel pipe to give protection during sensor probe installation. When the installation is complete, the outer 2" stainless steel pipe will be removed. The sight glass was mounted to a blind flange and the blind flange mounted to the existing flange on the cold-end of the spacer. An optical housing was machined so that the polarizer and collimator are given 6-dimension freedom of adjustment. The optical housing was connected to the spacer with a machined adaptor plate. The fiber connected to the collimator is fixed with a fiber cable clamp to ensure that the position of the collimator is not disturbed.

Figure 4.7. Mechanical packaging design (probe).

Figure 4.8. Design of metal reduced coupler.

Figure 4.9. Design of tapered screw.

Figure 4.10. Design of optical housing

Table 4-2. Components ordered for probe packaging.

Name	Material	Length	Diameter	Price	Vendor
Single bore cast alumina tube	99.8% alumina	60"	7/8" OD 5/8" ID	281.94	Tech Ceramics
Single bore cast alumina tube	99.8% alumina	24"	1 3/4" OD 1 1/2" ID		Tech Ceramics
Single crystal sapphire tube	Single crystal sapphire	12"	1.22" OD 1.04" ID		Saphikon
Single crystal sapphire tube	Single crystal sapphire	12"	1.02" OD 0.91 ID		Saphikon
1 pint high temperature ceramic glue (903HP)	98% Al ₂ O ₃				Cotronics
316L stainless steel pipe	316/316L				McMaster
316L stainless steel pipe	316/316L				McMaster
Reduce coupling	316/316L				McMaster
Iron pipe	Iron				McMaster
Pressure sight glass	1000psig, 600F rated				J. M Canty
Fiber feedthrough	1000psig, 600F rated				Conax Buffalo
Metal reduced coupler	316/316L				Maco Tool
Metal reduced coupler	316/316L				Maco Tool
Taper screw	316/316L				Maco Tool
Optical housing adaptor plate	Iron				Maco Tool
Optical housing	Iron				Maco Tool
600um fiber patch cord	600um core fiber	3m			Ocean Optics

During field test installation, the spacer will be mounted to the nozzle through a 4" raised face flange. The sight glass will act as the first pressure boundary. The spacer could be nitrogen purged to cool the spacer down and drive the possible moisture away from the sight glass or the inlet and outlet can simply be plugged. The fiber feedthrough will occupy one of the wiring inlets. The fiber cable inside the bell jar has a 200 μ m core fiber for LED power delivery and 6 $\times$ 200 μ m core fiber bundle for signal power feedback in two legs. The 200 μ m leg is connected to the fiber feedthrough port with 200 μ m core fiber which has the same NA (0.23) through ST connector and adaptor. The 6 $\times$ 200 μ m leg is connected to the fiber feedthrough port with 600 μ m core fiber, which has the same NA (0.23) through SMA905 connector and adaptor. Two fiber patch cords with 200 μ m core fiber and 600 μ m core fiber are connected to the fiber feedthrough outside port via adaptors and the other ends of the patch cords are connected to the LED and spectrum card on the sensor electronics box. A thermocouple will occupy another inlet. The thermocouple monitors the temperature inside the bell jar. If the sight glass fails, and the temperature increases drastically and exceeds the threshold, the thermocouple controlled nitrogen purge valve will open, and a 500psig

nitrogen purge will push the hot gas back into the coal gasifier. This is the second pressure boundary. Pictures of the sensor probe after machining is shown in Figure 4.11 through Figure 4.18.

Figure 4.11. Spacer welding seam and two pairs of purge inlets

Figure 4.12. Inner alumina tube with maximum length sapphire tube protection; Close up of the sapphire tube protection

Figure 4.13. Stainless steel sensor probe support pipe; close up of reducing coupling; close up of taper.

Figure 4.14. Close up of reduced coupler welded to the end of the spacer; sensor support pipe screwed into the reduced coupler on the spacer.

Figure 4.15. Taper screw side view and, top view, machined bolt threads on the flange and the taper screw; close up of machined bolt threads on the flange and the taper screw.

Figure 4.16. Sight glass from J. M. Canty; machined sight glass mounting flange; sight glass mounted on the spacer.

Figure 4.17. Optical housing.

Figure 4.18. Fiber feedthrough.

5.0 Sensor Electronics Design

The enclosure for the sensor electronics must satisfy National Electrical Code Class I, Division II, Group B requirements. If an AC power source is used, the enclosure must be nitrogen purged and explosion proof, requiring a very expensive metal box is needed. If DC power is used, the electronics are deemed intrinsically safe, and only a general-purpose enclosure is required. In this project, a DC power source was chosen.

The environment close to the coal gasifier is in open air. The temperature variation is large. There is no available AC power, and the current dissipation of the computer exceeds 1 amp and it not a safe device for Class I Div II Group B environment. Therefore it is not suitable to place the sensor data processing computer anywhere near the coal gasifier. Instead, the computer will be placed in the control room on the 3rd deck of the building, which is 520ft from the sensor mounting location on the 4th deck. The control room is ventilated and has power supply and Internet access. Computer control and sensor data transfer will be realized through a device called a USB extender. The USB extender enables the data transfer from a remote USB device to the computer which is at most 2km away. The USB extender data link is shown in Figure 5.1. The two USB extender units are connected through a MT-RJ multimode fiber cable. The cable length is 520ft.

Figure 5.1. System topology of the sensor data acquisition system.

To eliminate optical signal degradation through the blackbody radiation effect, on-off modulation of the LED was adopted. A USB module will function as the modulation block. The USB module gets on/off instructions from the computer via the USB extender, and then it controls the voltage on the PLD200 analog modulation pin. When a state switch of state occurs, the PLD200 flips the voltage on its status pin, and the voltage change is read by the USB module, and passed to the computer. Therefore, the modulation is realized in a closed loop.

The other two components in the electronics box are the Ocean optics spectrum card which is powered by the USB extender, and the PLD200 LED driver. A block diagram of the sensor electronics is shown in Figure 5.2. The power source is a power line provided by Wabash River Energy with 28VDC and 1A maximum connected to the electronics enclosure. A surge protector is used to prevent damage to the electronics in the box by a voltage surge of the power line. The 28VDC is fed to the 28VDC/15VDC and 28VDC/5VDC converter. The heart of the converter is an integrated voltage controller. The 15VDC is then fed to the USB extender remote unit. The USB extender drives the Ocean Optics spectrum card and USB module via USB ports. The 5VDC is fed to the PLD200 LED driver. The computer communicates with the spectrum card and USB module via the USB extender set.

Figure 5.2. Block diagram of the sensor electronics.

The power dissipation of the electronics box is 28VDC and 0.37A at maximum. The dimension of the electronics box is 13" X 8.3" X 5.3". The material is aluminum. A electronics equipment list is shown in Table 5-1. A picture of the electronics box is shown in Figure 5.3.

Figure 5.3. Electronics enclosure.

Table 5-1. Components in the electronics box.

Name	Function	Price	Vendor
Spectrum Card	Convert the optical measurand into electrical format		Ocean Optics
PLD200 LED driver	LED driver. Provide correct voltage and current to drive the LED. Enables modulation of the LED.		
LED	850nm LED		
USB module	On-off modulates the LED. Read the on-off status of the LED and feedback to the computer		
USB extender	Enables the computer to communicate with the USB module and the spectrum card as a local USB device		
Surge protector	Protect the electronics from damaging		
28VDC/15VDC converter	Converts the power format for the USB extender		
28VDC/5VDC converter	Converts the power format for the PLD200 LED driver		
Switch	Power switch of the electronics box		
Indicators	A group of LED indicators that reads the status of the electronics box		

6.0 Software Algorithm Design

The signal to blackbody radiation ratio at high temperature is very small, approximately 1/30. To extract the signal from the large background, LED on-off modulation was adopted. The algorithm flowchart is shown in Figure 6.1. The other problem related to the large blackbody radiation induced background is that very low spectrum card integration time has to be used to prevent the CCD array from saturation, for example, 2ms. This results in small signal power compared to system noise. In other words, low signal to noise ratio. To improve this, the blackbody radiation subtraction loop is performed N times so as to increase the signal to noise ratio by $\sqrt{N}$ according to communication theory. For example, $N=100$ would give us 10dB increase in S/N. The algorithm flowchart is shown in Figure 6.2. The timing of the algorithm is shown in Figure 6.3. The LED is given M seconds to cool down. The software gives a temperature value every N loop plus M seconds.

Figure 6.1. Flowchart of the blackbody radiation extraction algorithm.

Figure 6.2. Flowchart of the improved algorithm.

Figure 6.3. Time sequence of the software algorithm.

7.0 Field Test Installation Procedures

The sensor field test installation has been broken down into several steps as follows:

1. Sensor probe ship to Wabash River Energy: Ship the sensor parts disassembled in a van.
2. Sensor probe assembly: Assemble the sensor probe to the spacer, and install the spacer onto the nozzle.
3. Sensor probe adjustment: Adjust the collimator and polarizer position to obtain the best optical signal on a laptop.
4. Cover the bell jar: Connect the fiber bundle to the fiber feedthrough, cover the bell jar, and connect the two fiber patch cord to the fiber feedthrough. Use the laptop to obtain a good quality signal.
5. Wire installation: Set the fiber cable up; connect the electronics box with the power line
6. Obtain the signal in the control room.
7. Obtain the signal at Virginia Tech.
8. Coal gasifier fireup.
9. Start recording data.

8.0 Sensor System Design and Remote Data Access

A phone line was installed at Wabash River Energy for use as the remote data acquisition line. A client version of the PcAnywhere program was installed on the sensor computer. The sensor computer is connected to the internet using 56kbps modem. Personnel at Virginia Tech have a computer with T1 LAN connection to the internet and the server version of the PcAnywhere program. The software allows remote data acquisition and control of the sensor computer. Another phone line was installed for the Powerstone AC power remote controller in case of deadlock of the sensor computer. With Powerstone (Figure 8.1), personnel can reboot the sensor computer remotely at Virginia Tech.

Figure 8.1. Powerstone remote power controller.

9.0 Conclusions and Future Work

The main objective of this project is to bring the BPD sensor technology, which has already been demonstrated in the laboratory, to a level where the sensor can be deployed in the harsh industrial environments and will become commercially viable. Research efforts were thus focused on preparing all the necessary components for field testing, including sensor probe design and fabrication, mechanical packaging, laboratory testing, electronics design, software algorithm development, installation procedures, and remote data access. Installation of the temperature sensor in the gasification facility will proceed in about one month. The system will be operated for several months to evaluate the performance. The data obtained during the field test will be analyzed to determine the performance of the temperature sensor in the gasification unit.

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List of Acronyms and Abbreviations

A/D, analog to digital
APP, Advanced Pressure Products, Inc.
BPDI, broadband polarimetric differential interferometry
CCD, charge couple device
CPT, Center for Photonics Technology
CTE, coefficient of thermal expansion
EFPI, extrinsic Fabry-Perot interferometer
EMI, electromagnetic interference
FWHM, full width half maximum
GPM, gallons per minute
GRIN, graded index
ID, inner diameter
LED, light emitting diode
MMF, multimode fiber
OD, outer diameter
OPD, optical path difference
PC, personal computer
PZT, lead zirconium titanate
RFLWN, raised face long weld neck
SCIIB, self-calibrated interferometric/intensity-based
SLED, superluminescent light emitting diode
SMF, single mode fiber
SNR, signal to noise ratio
VTPL, Virginia Tech Photonics Laboratory (now Center for Photonics Technology)