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Laser Ultrasonic Furnace Tube Coke Monitor

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1.0 INTRODUCTION

This report summarizes the technical progress achieved during the first quarter of the ERIP project entitled, "Laser Ultrasonic Furnace Tube Coke Monitor." The focus of work during this reporting period was the procurement and initial testing of ultrasonic test instrumentation needed to investigate non-optical pulse generation at the surface of a simulated furnace tube. Initial testing confirmed the ability to resolve the presence of a coke deposit on the surface of a simulated furnace tube using a 5 MHz piezoelectric transducer operating in the pulse echo mode.

In the next quarter, work will focus on the development of hardware and software interfaces to enhance and automate the signal processing of the coke layer pulse echo, and the development of optimum methods for mechanical pulse generation, including harmonic excitation using an impactor and pulse generation using a high temperature stand-off transducer.

2.0 BACKGROUND

The overall aim of the project is to demonstrate the performance and practical use of a laser ultrasonic probe for measuring the thickness of coke deposits located within the high temperature tubes of a thermal cracking furnace. This aim will be met by constructing an optical probe that will be tested using simulated coke deposits that are positioned inside of a bench-scale furnace. Successful development of the optical coke detector will provide industry with the only available method for on-line measurement of coke deposits.

The optical coke detector will have numerous uses in the refining and petrochemical sectors including monitoring of visbreakers, hyrotreaters, delayed coking units, vacuum tower heaters, and various other heavy oil heating applications where coke formation is a problem. The coke detector will particularly benefit the olefins industry where high temperature thermal crackers are used to produce ethylene, propylene, butylene and other important olefin intermediates. The U.S. is the world's largest ethylene producer and accounts for about 30% of the total world production with a product value of over 10 billion dollars.

The ethylene industry requires development of an on-line method for gauging the thickness of coke deposits in cracking furnaces because the current lack of detailed knowledge of coke deposition profiles introduces the single greatest uncertainty in the simulation and control of modern cracking furnaces. The laser ultrasonic coke detector will provide operators with valuable new information allowing them to better optimize the decoking turnaround schedule and therefore maximize production capacity. Precise information on coke deposit thickness will allow selection of the optimum cracking severity for maximizing effective annual yield of ethylene. The detector will provide information on unusual laydown patterns which might be attributable to burner

misalignment, nonuniform feed distribution, or other maladies. The detector will provide new insight on the mechanism of coke formation and will enhance our understanding of methods to minimize the rate of coke growth.

There is a substantial demand for a reasonably priced instrument capable of measuring coke deposits in cracking furnaces. As there exists no competing technology, a technically proven instrument would likely become a standard monitoring tool for cracking facilities. The instrument offers the potential for improving furnace energy efficiency, optimizing production capacity, and maximizing tube life. The coke detector has significant application for both commerce and research.

To assist in the development and commercialization of this important instrument, discrete project steps are proposed which will progress from subcomponent development to testing of an integrated detector probe. These discrete steps are: 1) design and fabrication of mechanical pulse generator, 2) characterization of the pulse generator using conventional contact ultrasonics, 3) integration of the pulse generator and a laser ultrasonic detector within a probe device, 4) cold testing of the integrated laser ultrasonic probe, and 5) hot testing of the probe under simulated furnace conditions. Successful completion of these steps will satisfy the overall aim of the project which is to demonstrate the practical use of the optical coke detector for furnace monitoring applications.

3.0 PROJECT OBJECTIVES

A key project objective will be to verify that the optical probe can meet specific end-user criteria needed for successful commercialization of the device including the following:

1. Sensitive measurement of coke deposits ranging in thickness from 0-1/4"
2. Suitable for use on coils of 1 1/2"-4" diameter
3. Suitable for use at coil temperatures up to 1050°C
4. Suitable for use on rough oxidized metal surfaces
5. Instrument reliability under practical operating environments
6. Measurement reproducibility
7. The instrument is operator safe
8. The probe can be used to make random measurements down the coil length at various access angles from available furnace ports
9. The probe can operate at stand-off distances of at least 10-20'
10. The instrument package can be assembled for less than \$50,000-\$75,000

Testing of an all-optical coke detector, consisting of a pulsed laser and a laser ultrasonic detector, was performed under a DOE/SBIR Phase I program. The Phase I test program verified the technical feasibility of the device, but determined that energetic and costly lasers would be needed to implement the concept in an industrial furnace. The all-optical coke detector also raised concerns regarding operator safety, measurement flexibility, and potential furnace tube damage due to the high power density of the pulsed laser needed for

sensitive measurement. Thus, it was concluded that basic technical design modifications would be needed to reduce the cost, enhance the safety, and improve the utility of the coke detector if it was to be widely adopted by industry.

To overcome the deficiencies of the all-optical coke detector design, an alternative configuration was developed based on the use of an insertable probe. The probe consists of a mechanical pulse generator and a fiber optic detector. The probe is physically inserted into the furnace box where it briefly contacts the furnace tube wall. Upon contact, a mechanical pulse is generated at the outer surface of the tube wall. The pulse travels through the tube wall and into the coke layer where it is backscattered. An optical fiber contained within the probe conveys reflected laser light from the tube surface to an interferometer which detects the pulse echoes that are backscattered from the coke layer. By deleting the pulsed laser from the coke detector design, the size, cost and complexity of the device is substantially reduced. By collecting reflected light near the tube surface using an optical fiber, an inexpensive, low power detection laser can be employed.

The main technical objectives will be to optimize the method of pulse generation and to confirm the sensitivity of monitoring pulse echoes using a commercially available, low power, and relatively inexpensive fiber optic laser interferometer. Specifically, the technical objectives will include:

1. Develop optimum method for non-optical excitation or pulse generation at the tube surface. The proposed methods to be investigated will include: a) harmonic excitation using an impactor, and b) pulse generation using a stand-off piezoelectric transducer. The wave response for each generation technique will be characterized initially using contact transducers and later using laser ultrasonics. The generation techniques will be applied to simulated coke deposits at ambient temperature.
2. Testing of mechanical pulse generator integrated with laser ultrasonic fiber optic detection head in a probe tip. Working probes will be constructed including both mechanical actuator and laser ultrasonic optics. The probe will be tested on simulated coke deposits at ambient temperature to verify the basic performance and method of use of the coke detector probe under controlled conditions.
3. Hot Testing. A prototype detector consisting of a water cooled lance and a probe tip with mechanical actuator and integrated optics will be tested in a simulated combustion furnace at temperatures of approximately 1000°C. The test will be performed using simulated furnace tubes containing coke deposits of varying thicknesses. The ability to detect coke layer echoes will be demonstrated under the high temperature conditions similar to a commercial cracking furnace.

The results of the project should provide a firm basis for optimizing a commercial prototype coke detector which will be demonstrated in a thermal cracking furnace at a commercial petrochemical facility.

4.0 PROJECT WORK

A broadband ultrasonic pulser/receiver instrument (Model 5072R) was purchased from Panametrics of Waltham, MA. The pulser section of the instrument generates a short duration electrical pulse of controlled energy that excites an ultrasonic transducer to produce a short duration ultrasonic pulse. In the pulse-echo mode, a reflected pulse is detected by the receiving transducer to produce a voltage signal that is amplified and displayed on a digital oscilloscope. A general purpose 5 MHz transducer and a stand-off transducer designed for high temperature applications were also procured.

In proposed measurement concept, the ultrasonic wave is generated at the outside surface of the tube. The wave travels inward where it is partially reflected at the interface between the metal wall and the coke layer to produce the first pulse echo wave. A portion of the wave energy is transmitted into the coke layer where it reflects at the inner surface of the coke layer to produce the second pulse echo wave. Additional internal reflections within the metal layer and the coke layer produce additional pulse echoes that diminish in amplitude due to attenuation. The time differential between the first and second pulse echoes provides specific information on the thickness of the coke layer.

To test the ability of the ultrasonic test equipment to distinguish the pulse echo from the coke layer of a simulated furnace tube, a 1/8" (3.175 mm) thick isostatically molded graphite slab was machined and bonded to the surface of a 3/8" (9.52 mm) Incoloy 800H plate. The graphite sample was supplied by SGL Carbon Group located in St. Marys, Pennsylvania. The dimensions of the graphite slab and the Incoloy plate were selected to be representative of the thickness of the coke and tube metal wall layers of a thermal cracking furnace about mid-way through the thermal cracking cycle. The test sample is shown in Figure 1.

Figure 1. Test Specimens

Previous testing has established the longitudinal wave velocity of the metal alloy and the isostatically molded graphite to be 5.67 mm/ μ sec and 2.55 mm/ μ sec. Therefore, the thickness of the coke layer should be predicted as:

$$x_c = (t_c - t_m) v_c / 2 \quad (1)$$

Where x_c is the coke thickness (mm), t_c is the first coke layer pulse echo time (μ sec), t_m is the first metal layer pulse echo time (μ sec) and v_c is the longitudinal wave velocity in the coke layer (mm/ μ sec).

Alternately, when the coke and metal layer thickness are known, then the time difference ($t_c - t_m$) is given by:

$$(t_c - t_m) = 2 x_c / v_c \quad (2)$$

For the test sample, the theoretical time difference is:

$$2 (3.175 \text{ mm}) / (2.55 \text{ mm}/\mu\text{sec}) = 2.49 \mu\text{sec}$$

Test conducted using the instrumentation shown in Figure 2, confirmed the ability to detect the first pulse echoes from the metal wall and the coke layer and that the measured time response closely conformed to equation (2).

Figure 2. Ultrasonic Test Instrumentation

Software is being developed to download information from the digital oscilloscope for signal processing that will allow automatic calculation of the coke layer thickness for any arbitrary sample.

In the next phase of testing, measurements will be repeated using a stand-off transducer that is capable of contacting high temperature surfaces for brief periods of time. Also, alternate mechanical actuators, such as shown in Figure 3, are under development to generate a high-energy pulse that decays into harmonic waveforms that depend on coke thickness. Deconvolution of the signal response will be investigated in the next period.

Figure 3. Mechanical Pulse Actuator

5.0 PROJECT SCHEDULE AND BUDGET

Significant technical progress has been made toward completing the Task 1 objectives. The project expenditures to date are approximately \$7,500, and the expenditures are consistent with the technical progress of the project.