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High temperature Fabry-Perot-based strain sensor for ceramic barrier filters

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ABSTRACT

We report results from a program to develop fiber-optic sensor-based instrumentation methods to allow the in-situ analysis of ceramic barrier filters. The sensor used was an extrinsic Fabry-Perot cavity created between the ends of two longitudinally aligned fibers. Filters instrumented with these fiber sensors were tested in a combustor simulator at the Westinghouse Science and Technology Center. These tests were performed using silica optical fibers capable of withstanding the high temperature and harsh chemical environment of the combustor. The single-ended approach of the reflective Fabry-Perot sensors is well suited for high thermal strain measurements. The results from several tests are presented.

2 INTRODUCTION

The Westinghouse Science and Technology Center (STC) is currently developing ceramic barrier cross flow and candle filter systems for advanced fossil power generation applications. Current filter development efforts have utilized mathematical models to predict in-service stressing of filters to improve filter life and reliability. The models depend on estimating certain heat transfer and physical property parameters that are not well defined. There is a need to substantiate and refine this analysis with in-situ sensors. Optical fiber sensors have shown to be the only available technology capable of measuring strain and stress in the high-temperature flyash environment of a boiler. The purpose of this program is to utilize improved, high temperature, optical fiber sensors to measure the in-service stressing that occurs in ceramic barrier filter systems, thereby providing valuable input to the optimization of filter processing and operation.

2.1 The basic sensor

The optical fiber sensors used for the tests are based on the design developed by Va Tech under the Department of Energy/Morgantown Energy Technology Center (DOE/METC) Smart Structures for Fossil Energy Applications contract. Briefly, the sensor is commonly known as an extrinsic Fabry-Perot interferometer (EFPI) and is shown in Figure 1a.¹ For a displacement sensor it is useful to plot the detected intensity versus gap-separation 's', as shown in Figure 2a. We see that the fringe contrast drops as the displacement increases, which is to be expected since the relative intensity of the sensing reflection starts dropping with respect to the reference reflection.

If we define 's' to be equivalent to the change in length, ΔL , of a material under stress, then from the number of fringes, one can deduce the amount of strain, $\Delta L/L$, where 'L' is the gauge length of the sensor. We can define $\Delta L = 1/2 \lambda$ (# of fringes), where ' λ ' is the wavelength of light. The EFPI sensor was bench tested for a comparison with theoretical results. A micropositioner was used to create a known displacement between the two fiber ends that form the Fabry-Perot cavity, and an oscilloscope trace was recorded of the continuously monitored output intensity of the. The recorded trace for a

starting gap of zero to a final gap of 203 microns is shown in Figure 2b. The experimentally counted number of fringes for a displacement of 202 microns was 301.5. From a theoretical calculation, the gap for this was 312.3, or approximately 3% difference.

For thermally induced strain, the number of fringes can be predicted to be

$$\# \text{ of fringes} = \frac{2l(\Delta T)\alpha_{\text{filter}}}{\lambda} \quad (1)$$

where ΔT is the change in temperature and α_{filter} is the thermal expansion coefficient of the filter. From this, the expected strain of the filter at the measurement position can be predicted.

This cyclic output introduces a difficulty in monitoring the direction of the strain. To overcome this, a dual interferometer approach is introduced where the outputs are 90°(quadrature) phase-shifted from each other. To achieve quadrature outputs, two sensors were placed side-by-side in close proximity to each other, with the phase of the output of one of the sensors biased 90° with respect to the other. Figure 1b shows this sensor configuration.

2.2 Gold-coated fiber sensors

Regular fiber coatings are usually made from organic materials which can only withstand temperatures below 300°C. Since the testing in this program required effective operation at 850°C or higher, a high-temperature gold-coated fiber manufactured by Fiberguide Industries was chosen. The highest operating temperature suggested by the manufacturer for long-term use is 750°C, the softening point of gold, but because we are interested in temperatures higher than the recommended level, the gold coated fiber was first tested in the laboratory at high temperature. The fiber was placed into a kiln and the temperature was raised gradually up to 900°C. The fiber remained at 900°C for two hours and then the temperature was reduced gradually to room temperature. After checking the fiber, no significant change in mechanical properties was observed.

The first gold fiber EFPI sensor was then built and tested. The gold coating was removed from the sensor lead by an aqua regia solution at its attachment point to the filter material, as is shown in Figure 3. The sensor was attached onto the surface of a ceramic filter using a high temperature 905 Cotronics inorganic adhesive. As the sensor was subjected to a temperature ramp approaching 400°C, the sensor failed. Post inspection found a crack in the uncladded region of the lead fiber.

To prevent fiber breakage, a second sensor was built, which is shown in Figure 4. The lead fiber and the target fiber were all gold coated fibers. The outer diameter of the gold coated fiber was measured to be 158 μm , and special hollow core fiber with inner diameter of 166 μm was drawn to permit the gold fiber to be well guided but move freely. The sensor was tested and gave a good fringe contrast for a temperature increase from 25°C to 750°C. A similar result was also obtained for the decrease in temperature back to room temperature.

3 FILTER TESTING

Both ceramic barrier candle and cross flow filters have been instrumented and tested with gold fiber EFPI strain sensors. The tests were conducted at the Westinghouse STC pressurized fluidized bed combustor simulator. The purpose of the tests was to demonstrate both the viability of the sensors in the harsh coal-fired combustion environment and the capability of monitoring filter parameters during operation.

3.1 Test one

The first test was the first integration of sensors on a 1.5 m-long candle filter. Sensors were located near the flange, in the middle, and at the end of the filter, both on the exterior surface (dirty side) and the interior surface (clean side). For the attachment of the sensor on the clean side at the end, two 12.7 mm holes were drilled in the filter at the end; these holes

were later plugged with ceramic adhesive after the sensor was attached. Also from the point of entry into the combustor simulator to the sensor region, annealed stainless steel tubes were placed over the fiber leads. These tubes provided mechanical and chemical protection for the fibers. The final configuration of the instrumented filter can be seen in Figure 5. This figure also shows the strategy of the sensor bonding. A hollow glass tube, the same type as was used for the optical fiber sensors, was placed at the opening of the steel tube in order to allow unrestricted movement of the fiber due to thermal expansion while simultaneously maintaining the pressure seal. Figure 6 shows a photograph of the completed filter before the test.

On the day of the test, the filter was loaded into the simulator, and the simulator was prepared for the test. In an attempt to detect strains due to the clamping of the filter into the tube sheet, Sensor 4, was interrogated during the procedure. The sensor output during the clamping procedure can be seen in Figure 7a. After the procedure was completed, the candle filter was pulled and pushed to provide a calibration output. This signal can be seen in Figure 7b. A comparison of these figures yields only a 1/4-fringe difference in sensor outputs during the clamping procedure, implying that very little axial strain was induced during the clamping.

This test was piggy-backed onto a high-temperature candle filter test, reaching operating temperatures for this test reached 930°C. The EFPI sensors did not survive the entire test due to insufficient adhesion to the filter, but they did provide useful information while in operation. For example, an indication of the thermal transfer effects through the wall of the candle filter can be seen from a comparison of sensor 3 (dirty side) and sensor 4 (clean side). Figure 8 shows the fringe count of both sensors over time compared to the ambient (dirty side) temperature.

The determination of strain from the fringe count was more difficult. Unexpected results led to an investigation of the sensor configuration. We suspect that a complication was introduced with the addition of the gold coating on the silica fiber in the sensor region. To determine strain, one measures the change in gap, ΔL . However, the change in gap is dependent on the thermal expansion of the sensor fiber, as well as the thermal expansion of the filter. Any expansion of the sensor fiber tends to reduce the gap as the expansion of the filter tends to increase the gap. Previous tests with strictly silica sensors have relied on the fact that the coefficient of thermal expansion (CTE) of silica is an order of magnitude less than the filter material. With the introduction of the gold coating on the fiber in the sensing region, however, the CTE of the sensing fiber is altered and is unknown. It is suspected that the CTE is somewhere in between pure silica and pure gold, but efforts to model the thermal expansion have been inconclusive, due partially to a lack of existing reference data for the materials at the high temperatures of interest. Post inspection of lead fiber subjected to the first test showed a clear delamination of the gold coating from the silica. This supports the uncertainty with the data. Because of these difficulties, subsequent tests used the original sensor design, having all of the gold stripped off the fiber in the sensing region, this time mechanically.

3.2 Test two

The cross flow filter test concentrated the sensing on one area of the filter and attached sensors inside both the dirty and clean channels. A corner area on one of the faces of the filter was picked, as can be seen in Figure 9, and a combination of quadrature phase-shifted and single sensors were attached in close proximity to each other. In the final configuration, two single strain sensors were placed in channels on the clean side, with two more placed opposite them in dirty side channels. Three other sensors were attached on an exterior face in the vicinity of the channel sensors. All three of these were phase-shifted sensors.

Figures 10a and 10b show the responses of sensors 1 and 4 throughout the testing of the first day. During the first cool-down period of the test, one of the legs of sensor 1 appeared to get stuck, producing no noticeable signal in a few degree range of 325°C. The sensor leg then became active again as the temperature dropped below this range. On the second temperature increase, the same phenomenon occurred in a few degree range of 332°C. This occurred a third time in the same region when the combustor was cooled for the second time. These points are indicated in Figure 10a by the numbers 1, 2, and 3. It was not possible to determine a cause for this phenomenon through post-test inspection of the sensor, however. On the second day of testing, the combustor was heated to approximately 837°C from a residual temperature of 150°C. Figures 11a and 11b show the responses of sensors 1 and 4, respectively. The figures indicate that both sensors experienced

a large rate of sensor gap separation, sensor 4 beginning at approximately 480°C and sensor 1 at approximately 590°C. Since the sensors were placed across clean-side filter laminate seams, this data seems to indicate that a delamination occurred, starting from the bottom of the filter. Post-test inspection of the filter, however did not show any delamination in that area, although cracking did occur in other areas of the filter.

4 CONCLUSIONS

Optical fiber strain sensors have been fabricated to withstand the harsh environment of fossil fuel power plant combustors. Gold-coated EFPI sensors were bonded to both ceramic barrier candle and cross flow filters and subjected to simulated high temperature, high pressure conditions of a fluidized bed combustor. Even though the tests operated beyond the recommended temperature levels of the gold-coated fiber, the sensors performed well. The sensors tracked the thermal expansion of the filters, although adhesion problems caused many of the sensors to fail before the completion of a full filter test. Further work is in progress to correct the adhesion problems and perform additional tests to demonstrate sensor capabilities. Future efforts are planned to perform filter diagnostics in the field and apply the sensors to other fossil power plant applications.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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Figure 1a The Extrinsic Fabry Perot Interferometer (EFPI).

Figure 1b The Quadrature Phase Shifted (QPS) EFPI.

Figure 2a Theoretical output versus gap separation.

Figure 2b Output intensity of EIPF as displacement was changed from 0 to 203 microns.

Enlarged View of the Sensor Lead

Figure 3 Sketch of gold coated fiber based EFPI.

Figure 4 Configuration of gold coated fiber based EFPI sensor head.

Figure 5 Sketch of instrumented candle filter showing placement of sensors. Inset: Attachment of sensor to filter

Figure 6 Photograph of instrumented candle filter before the test.

Figure 7a Output of sensor #4 when candle filter was being clamped.

Figure 7b Output of sensor #4 due to pushing and pulling of the installed candle filter.

Figure 8 Microstrain of candle filter measured by sensors #3 and #4.

Figure 9 Sketch of instrumented cross flow filter showing placement of sensors.

Figure 10a Microstrain and time versus temperature plot for sensor #1 on the first day.

Figure 10b Microstrain and time versus temperature plot for sensor #4 on the first day.

Figure 11a Microstrain and time versus temperature plot for sensor #1 on the second day.

Figure 11b Microstrain and time versus temperature plot for sensor #4 on the second day.

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