DEVELOPMENT OF NONDESTRUCTIVE EVALUATION METHODS
FOR STRUCTURAL CERAMICS*

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ABSTRACT

During the past year, the focus of our work on nondestructive evaluation (NDE) methods was on the development and application of these methods to technologies such as ceramic matrix composite (CMC) hot-gas filters, CMC high-temperature heat exchangers, and CMC ceramic/ceramic joining. Such technologies are critical to the “Vision 21 Energy-Plex Fleet” of modular, high-efficiency, low-emission power systems. Specifically, our NDE work has continued toward faster, higher sensitivity, volumetric X-ray computed tomographic imaging with new amorphous silicon detectors to detect and measure axial and radial density variations in hot-gas filters and heat exchangers; explored the potential use of high-speed focal-plane-array infrared imaging technology to detect delaminations and variations in the thermal properties of SiC/SiC heat exchangers; and explored various NDE methods to characterize CMC joints in cooperation with various industrial partners. Work this year also addressed support of Southern Companies Services Inc., Power Systems Development Facility, where NDE is needed to assess the condition of hot-gas candle filters. This paper presents the results of these efforts.

INTRODUCTION

Nondestructive evaluation (NDE) technology is being developed to advance the reliable application of ceramic materials to fossil energy systems for improved efficiency and better environmental control. Advanced materials systems under development for fossil energy applications include continuous-fiber ceramic matrix composites (CMC) for hot-gas filters and heat exchangers. Part of this work includes development of methods to join CMC materials for the fabrication of large components.

NDE methods to detect and measure variations in the axial and radial density of hot-gas filters and heat exchangers are being developed. These methods are needed to detect changes in density for process control during fabrication, study the efficiency of back-purging during cleaning, and detect damage in situ, if possible. Also under development are NDE methods to establish the quality of ceramic-to-ceramic joining in shop fabrication of parts with complex shapes and in field repair.

DISCUSSION OF CURRENT ACTIVITIES

HOT GAS FILTERS

The NDE development work on hot gas filters\(^1\)\(^2\) consisted of two main activities: participation in the analysis of filters from Southern Company Services, Inc., Power Systems Development Facility (PSDF) in Wilsonville, Alabama and initial development of the high speed volumetric X-ray computed tomographic (CT) imaging capability for fast, off-line inspection.

As part of the development work on pressurized fluidized bed combustion systems, Southern Company Services, Inc., PSDF completed a 1000-hr test run with a Westinghouse filtration system that was operating at a temperature of 1350°F; the filtration system is shown schematically in Fig. 1.

![Schematic diagram of Westinghouse filtration system at Southern Company Services, Inc., PSDF in Wilsonville.](image)

**Fig. 1.** Schematic diagram of Westinghouse filtration system at Southern Company Services, Inc., PSDF in Wilsonville.

The hot-gas filter system is a two-stack system with 36 candles in the upper stack and 55 candles in the lower stack. NDE methods are under development to detect cracks and, in general, assess the status of the hot-gas filters. Work at West Virginia University\(^5\) has been examining the potential of acoustic resonance as a method to assess the in-situ status of filters. Our work, to date, has not focused on in-situ methods but rather on off-line methods to assess production quality and to inspect filters after removal from service. Last year, we reported\(^4\) on the development of X-ray CT imaging\(^5\) for mapping axial density variation in as-produced hot-gas filters. In that work, two tubes from 3M with SiC coatings of various thickness were mapped for axial density, as shown in Fig. 2.

Alumina-mullite Candle Filter T-19, produced by isostatic pressing by the Coors Ceramic Company, was removed from the Wilsonville facility and examined by X-ray CT imaging. Figure 3 shows a photograph of Candle Filter T-19 on the X-ray CT scanner. The axial CT images of the candle that were obtained are shown in Fig. 4, along with a schematic diagram that shows the source of the cross-sectional images.
Fig. 2. Capability of high-resolution X-ray CT imaging to detect differences in SiC overcoat on 3M hot-gas filters: (a) schematic diagram of 3M filter; (b) X-ray CT images of 3M hot-gas filters, demonstrating detection of SiC coating variability.

Fig. 3. Photograph of Candle T-19 on new X-ray CT system, which has a high-spatial-resolution amorphous silicon X-ray area detector.
Fig. 4. X-ray CT image analysis of Candle Filter T-19: (a) schematic diagram showing scan locations and (b) CT images at Locations 1 and 4.

The CT image from Location 4 shows two throughwall radial cracks that are 180° apart. Thirty-four 0.5-mm-thick CT images were obtained in this region and viewed as a small 17-mm-long volume. A three-dimensional (3-D) image that shows the 17-mm-long 3D-X-ray CT image is shown in Fig. 5.

Three-dimensional X-ray CT imaging is powerful, but speed of data acquisition and time to reconstruct images has made it a somewhat costly NDE method. A critical limiting factor has been the lack of a high-speed, high-spatial-resolution detector. During this past year, a cooperative R&D agreement was entered into with EG&G Amorphous Silicon of Santa Clara, CA, to explore a new amorphous silicon X-ray area detector. This detector, 1024 x 1024 pixels at 16-bit dynamic range, should allow full imaging of 25-mm-long sections in 60 s.
HEAT EXCHANGERS

The work on heat exchangers this past year was primarily an interactive project with Oak Ridge National Laboratory (ORNL). Two heat exchanger tubes, CVI 1173 and CVI 1132, were infiltrated at ORNL by using forced thermal gradient CVI. The fiber architecture was a tubular braided sleeve made of 3M Nextel™ 312, an aluminaborosilicate fiber. Forced thermal gradient CVI was used to deposit a SiC matrix. The dimensions of the tubes were 30 and 31 cm long, 5.7 cm in diameter, with a nominally 6-mm-thick wall. NDE analysis by thermal imaging and X-ray CT imaging were conducted.

For the thermal image analysis, we placed a 12-mm-diameter, 25-cm-long, 6.4-kJ flash tube inside the tubes and the infrared camera outside the tubes. The test setup in Fig. 6 shows this arrangement. Infrared image data were acquired with an image size of 100 x 256 pixels, which covered an area of 19.5 x 50 mm (195 μm x 195 μm pixels). Cross-sectional diagrams of the tubes that were used to obtain these images are shown in Fig. 7. Note the presence of a small tapered region in Tube CVI 1132. This region shows up in the thermal images as a dark band because we did not account for this variation in thickness. The thermal diffusivity image data are shown in Fig. 8.

One problem that occurred during the thermal diffusivity analysis was the apparent area of a possible delamination (dark areas in the images). To examine this, we conducted an analysis by high-resolution X-ray CT imaging. The X-ray CT image data that were obtained (see Figs. 9 and 10, respectively, for CVI 1132 and CVI 1173), suggest that the thermal image data are not detecting a delamination. Close visual examination of the inside of the tube showed that areas where thermal imaging suggests a delamination appear to correspond to areas of a heavy coating on the inside and
that the coating thickness varied along the axial length of the tube as well as radially. It was subsequently determined that this was a variation in the thickness of the SiC overcoat.

Fig. 6. Thermal image analysis of heat exchanger tubes: (a) schematic diagram of setup and (b) photograph of thermal-diffusivity-image setup.

Fig. 7. Schematic diagram of SiC/Nextel™ 312 heat exchanger tubes that were used to obtain infrared image data.
Fig. 8. Thermal diffusivity images of heat exchanger tubes: (a) CVI 1132, (b) CVI 1173. (Note regions of heavy SiC seal coat i.e., dark areas on images).

Fig. 9. X-ray CT images of tube CVI 1173 at (a) Location 1, (b) Location 3, and (c) Location 4 in Fig. 7.

Fig. 10. X-ray CT images of tube CVI 1132: (a) Location 6, (b) Location 4, and (c) Location 1.
JOINING

Ceramic-to-ceramic joining methods are usually necessary for shop fabrication of parts with complex shapes, e.g., heat exchangers and for field repair. Although several joining architectures are potentially useful, as reported last year (4), e.g., lap joints, socket flanges, straight socket and conical joints, this year, we initiated work on "T" joints.

Regardless of the method that is used for joining, NDE methods are necessary to establish the completeness and quality of the joint. The development of NDE methods to study joint quality is part of the NDE work.

This work is being performed in cooperation with the continuous-fiber ceramic matrix composite program within the Department of Energy Office of Energy Efficiency and Renewable Energy/Office of Industrial Technology.

CONCLUSIONS

NDE technology for assessing hot-gas filters, although shown to be capable of detecting through-wall density variations, cracks, etc., must begin to more heavily emphasize in-situ capability with one-sided access. The NDE technology to determine completeness of infiltration for CVI-infiltrated preforms seems to be established. However, problems have arisen when thermal imaging was used to determine thermal diffusivity in these materials if they were covered with a nonuniform or heavy SiC overcoat. The use of NDE technology to assess joint quality is only beginning and extensive additional effort is necessary.

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