Development and Testing of a High-Speed Fiber-Based Pyrometer for TREAT

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INTRODUCTION

The capability to accurately measure temperature in test reactors is necessary for the development and testing of new nuclear fuels. Additionally, accurate experimental data is requisite for the calibration of fuel performance codes to provide confidence on their results. A standard technique to perform in-pile temperature measurements is through the use of thermocouples. Temperature measurements from thermocouples suffer from drift from radiation expose, fin effect, and gamma heating. Other temperature measurement techniques have been developed for in-pile applications such as LVDT based sensor, ultrasonic based sensors, and intrinsic fiber optic sensors to name a few examples. However, each of these are contact measurements which depend on the thermal response of the sensor. While attempts have been made to minimize sensor size to improve the time resolution of these sensors, they are inherently slow devices due to the required thermal response. Pyrometry is a method in which high-speed noncontact temperature measurements can be performed. High-speed noncontact temperature measurements are valuable for experimental testing in transient reactors such as the Trasient Reactor Test (TREAT) Facility at the Idaho National Laboratory (INL).

The work presented here is based on the development of an infrared (IR) pyrometer for temperature measurements of experiments in the TREAT facility. The pyrometer has potential to provide unprecedented data on the temperature evolution of fuel cladding during a transient test. This temperature evolution combined with other high-speed instrumentation, will provide important data on the sequence of thermal/thermal-hydraulic events leading up to fuel failure. In-pile IR temperature measurements present a unique set of challenges for instrument and mechanical design, data interpretation, and the pyrometry method of choice. Some of the work in the development of this pyrometer will be discussed here.

APPROACH

Some of the defining challenges facing a pyrometer deployment in TREAT are:

- Uncertainties introduced from alignment and positioning error of optical elements or fuel pin;
- Related to the previous, system calibration will be sensitive to exact positioning. The logistics of eventual test assembly need to account for this;
- Incorrect emissivity determination related surface radiation properties and geometry: diffuse/specular reflection properties of target, varying target emissivity (material oxidizing during experiment), cylindrical cladding target surface;
- Error introduced from background radiation from surrounding environment reflecting off target surface;
- Influence of water/steam by absorption, refraction, or scattering the light.

While these challenges are not unique to the nuclear materials testing applications, the harsh environment, limited access to the target, and overall material limitations make them much more challenging to overcome than more conventional pyrometer applications. These challenges have been the focus of this work. This summary includes results from autoclave testing of optical fibers under PWR conditions, to determine their possible applications.

Many factors influence the temperature measurements from a pyrometer, including but not limited to: alignment, target surface properties, and anything that influences transmission through the optical path. Many factors are also interrelated and will have significant interaction effects that can be different from their respective separate effect. A design of experiments factorial analysis is well-suited to evaluating the main and interaction effects of these factors.

The pyrometer was evaluated using a 2^5 factorial using 3 replications under each condition. Four of the factors deal with the alignment of the optical fibers and the fuel cladding. The 5^{th} parameter compares flat and curved surfaces. In general, the two treatment levels used in the design experiments are an “as-designed” condition and an “off-design” condition for each parameter. The measured outputs from the design of experiments are the pyrometer measured emissivity, un-corrected temperature, and corrected temperature. The order of experiments was randomized to reduce the influence of underlying uncontrolled factors on the results. The design of experiments was conducted according to the guidelines provided by Montgomery [1]. Additionally, temperature measurements made with the pyrometer and thermocouple are compared to over a range of temperatures are presented.

RESULTS

Experiment conditions require that the optical fibers must be capable of surviving the extreme conditions of PWR temperature and pressure. To obtain measurement of cladding surface temperature, part of the optical line would have to be located in the coolant and therefore survive and perform well in PWR conditions. To investigate fiber material behavior in this condition, five fiber samples were placed in the autoclave at PWR conditions (300° C and 15.5 MPa) for 24 hours. Micrographs of the fibers taken after the test can be seen in Fig. 1. All of the silica fibers tested showed significant degradation of the fiber. The aluminum and polyimide coatings were damaged sufficiently that they no longer protected the fiber. The copper coating survived the environment, but the silica was eroded at the exposed end of the fiber. The sapphire fiber had no visible damage from the exposure as seen in Fig. 1e. Therefore, sapphire is recommended to be used for applications involving PWR water environments.

a)
b)
c)
d)
e)

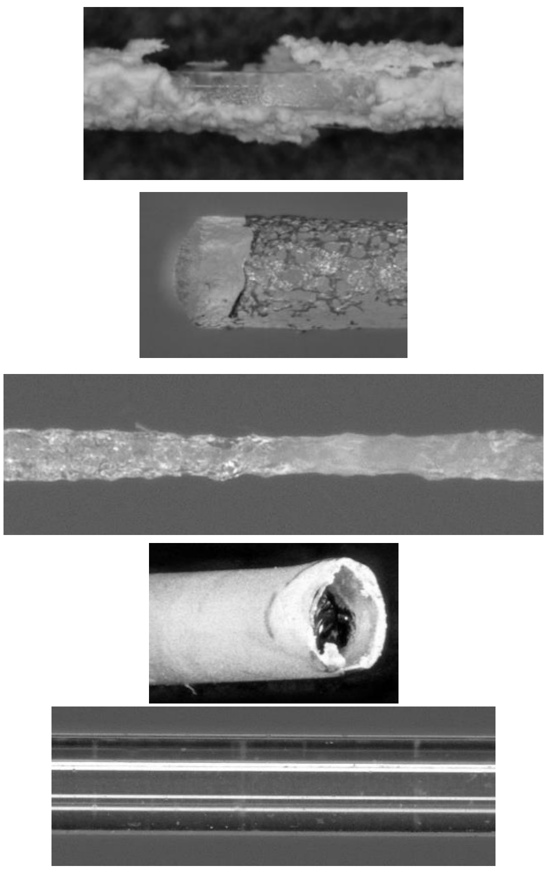

Fig. 1. Micrographs of optical fibers after 24 hours in the autoclave at 300° C and 2250 psi a) Aluminum coated silica fiber b) polyimide coated silica fiber c) bare silica fiber d) copper coated silica fiber e) sapphire fiber.

Several valuable results were obtained from the design of experiments. The main and interaction effects for each factor were determined. The un-corrected temperature output showed much less sensitive to several of the alignment parameters, compared to the emissivity and corrected temperature outputs. The un-corrected temperature also observed minimal interaction effects. The emissivity and corrected temperature had significant interaction effects between the majority of the parameters. This emphasizes the complex nature of the alignment, and how misalignment can influence temperature measurements.

A simple test was configured to measure cladding temperature was well aligned and calibrated. For the experiment, temperature and emissivity measurements were conducted over a range of temperatures. The pyrometer-measured temperature was plotted against the temperature read by the thermocouple on the surface of the rod. This plot of the temperature measurements is shown in Fig. 2. Both the emissivity-corrected and uncorrected temperatures are plotted. Good agreement is shown between the emissivity-corrected and the thermocouple measurements, which shows the advantage of the active pyrometer system.

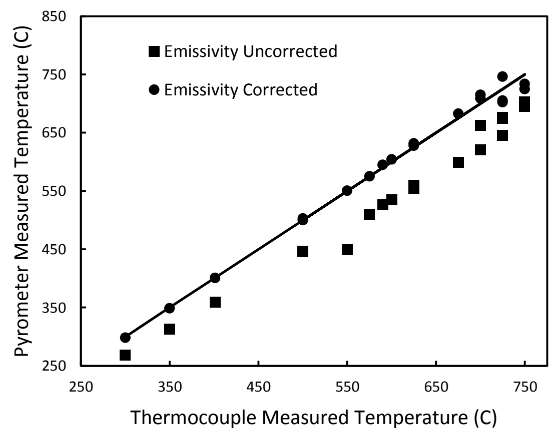

Fig. 2. Temperature measurements made by the pyrometry system compared to thermocouple measurements. The black line represents a line where the pyrometer and thermocouple would be in perfect agreement.

SUMMARY

A high-speed fiber-based pyrometer is under development at the Idaho National Laboratory for temperature measurements in the Transient Reactor Test (TREAT) Facility. A design of experiments has been conducted to evaluate the measurement sensitivity to factors such as alignment and sample surface characteristics. Autoclave testing of optical fibers under PWR conditions has been conducted to determine fiber survivability. Temperature measurements have been conducted using the pyrometer and compared to thermocouple measurements on sample surface, and they show excellent agreement.

REFERENCES

[1] Montgomery, D. C., 1997, Design and analysis of experiments, John Wiley & Sons.