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MEASURING TRANSIENT HIGH TEMPERATURE
THERMAL PHENOMENA IN HOSTILE ENVIRONMENT

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Measuring transient high temperature thermal phenomena in hostile environment^(a)

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Abstract

The design of equipment for measuring temperature and strain in a rapidly heated and pressurized cylinder of stainless steel is discussed. Simultaneous cinematography of the full circumference of the cylinder without interference with temperature and strain measurements is also illustrated. The integrated system uses a reflective chamber for the sample and requires careful consideration of the spectral energy distribution utilized by each instrument.

Introduction

Quantitative studies of material's response in severe transient environments require measurement of a variety of the sample's properties. This paper describes an instrumentation system which provides a photographic record of the sample's transient response and simultaneous temperature and dimensional measurements for reactor fuel cladding.

Description of experiment

The instrumentation system is for use with an experiment to be conducted by the Hanford Engineering Development Laboratory in which a piece of cylindrical nuclear fuel pin cladding is subjected to thermal and pressure transients sufficient to cause it to burst. The cladding is mounted in a vacuum chamber which is mounted in a small nuclear hot cell. Other characteristics of the materials test are:

- Sample - Stainless steel 316
 - Nominal diameter of 0.230 inch
 - Length 2-1/2 to 3 inches
- Test conditions
 - Transient test period of 1 second or less
 - Cladding temperature change from 250°C initial temperature to 1100°C final
 - Cladding internally pressurized using a hydraulic system
 - Strain anticipated (maximum values)
 - 1% for irradiated cladding
 - 50% for unirradiated cladding
- Environment
 - System must be suitable for installation in a small radiation hot cell (volume 2.5 m³)
 - Cladding radiation will be less than 5 R/hr at the cladding surface
 - Instrumentation must be suitable for use with the sample mounted in a vacuum chamber.

Conceptual instrumentation design goals:

- Cinematography
 - 10,000 frames/second during the transient test
 - 360° clear view of cladding surfaces
 - Permanent record of the transient clad performance
 - Optical resolution to enable visual location of cladding failures (within one 16-mm film frame)
 - Operation over total cladding transient temperature range
- Pyrometer
 - Provide reliable temperature measurements within the range of 500°C to 1100°C

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^(b) Operated by Battelle Memorial Institute.

- Data rate sufficient to accurately determine the time dependence of the cladding temperature
- Temperature errors of less than $\pm 20^{\circ}\text{C}$
- Operate without interference from the cinematography illumination and the strain sensor
- Extensometer
 - Capable of handling two strain ranges (1% and 50%) during the transient testing
 - Provide data that can be used to accurately determine the time dependence of the strain during a test
 - Operation free of interference from cinematography illumination and sample irradiance

Integrated design considerations

The requirement for the simultaneous photography, temperature and strain measurement places severe constraints on the measurement concepts and requires careful integrated system design. The requirements for this instrumentation are:

- Pyrometer or extensometer components within the chamber must allow a full 360° camera view of the sample surface.
- The cinematography illumination must not interfere with the operation of the pyrometer or the extensometer.
- The cinematography or the extensometer systems must be insensitive to the sample radiance.
- The extensometer illumination (an optical system was projected) must not degrade the performance of the cinematography system.

An infrared pyrometer and a non-contact optical extensometer were selected because both systems are compatible with these performance criteria.

Since the infrared pyrometer and optical extensometer do not require components near the sample, it is relatively easy to provide a compatible system design for the test chamber. The proposed configuration for the in-chamber components is shown in Figure 1. Each instrument allows an unhindered view of the sample for simultaneous observation.

Figure 1. Layout of test chamber.

Four mirrors are used to provide viewing of the total sample surface (360°) for high-speed photography. Two mirrors in the optical path of the frontal view compensate for the extra path length of the two systems used to view the rear of the fuel rod. The three optical path lengths are thus equal and give a single image plane for all three views. The mirrors are arranged so that the width of the window is minimized. The height of the window and mirrors is equal to the height of the fuel rod length of interest in the tests. The axis of the fuel rod is vertical.

A laboratory mock-up of the test chamber was fabricated to evaluate several illumination designs and the performance of the 360° cinematography mirror system. The model is shown in Figure 2 as seen from above the cinematography port. The other instrumentation ports are visible as well as the three segments of the cinematography image which give a 360° composite view of the cladding surface. The left, center, and right images correspond to the left rear, right rear, and front regions of the sample respectively. The circular hole in the left foreground was used to evaluate a lighting option and is not projected in the final design.

The chamber has access ports evenly separated around the chamber perimeter, a design feature which simplifies the signal and image transfer systems and interfaces with the radiation hot cell as shown in Figure 3. The periscopes or optical relays were designed to use existing ports in the hot cell. This design approach has the additional benefit that most of the optical and electronic components are located outside the hot cell which will improve performance and lifetime and make system maintenance significantly easier. The periscopes shown in Figure 3 can be simple image transfer systems which will be relatively inexpensive to design and fabricate. The cinematography periscope will utilize only flat windows and mirrors with the imaging elements located outside the hot cell.

Figure 2. Mockup of test chamber.

Figure 3. Plan view of hot cell.

The design of the cinematography illumination is a crucial element in this integrated measurement system. The illumination must support 360° cinematography of the sample while the spectral content of the lighting must not degrade the performance of the pyrometer or the extensometer. The very short exposure times associated with operation at 10,000 frames/sec require intense illumination. The illumination performance can be improved by making the chamber interior a highly reflective, diffuse material such as sandblasted aluminum or barium sulfate (BaSO_4). The reflective properties of these surfaces reduce losses within the chamber and improve the general illumination uniformity throughout the chamber. The diffuse nature of the chamber surface improves spatial uniformity of illumination by scattering light throughout the chamber. This type of surface also provides a significant benefit to the temperature measurements, as will be discussed later.

Instrumentation subsystem designCinematography

The requirement of a photographic record of the transient test at 10,000 frames/sec restricts the choice of camera to a rotating prism type and places stringent requirements on the sample illumination. A number of commercial 16-mm cameras will provide full-frame operation at 10,000 frames/sec. High-speed cameras have start-up periods during which a significant portion of the film in the magazine is expended before reaching terminal speed. Readily available models accommodate film magazines carrying only 400-450 feet of film and therefore do not allow full high-speed operation for significant periods of time. Most published specifications indicate that roughly 200 feet of film will be exposed before the camera reaches 10,000 frames/sec.

If the camera exposure is correctly adjusted for full-speed operation, then the film will be overexposed for the frames exposed during startup. The film consumed during start-up limits the full frame, 10,000 frame/sec operation to periods of one second or less. This limited operating time dictates that the camera and transient test sequence be carefully synchronized to insure that the film record includes the desired transient interval.

Most cameras can be purchased with a timing mark option which places an index mark on the film edge. This allows a precise correlation of the film record with externally recorded data. Two marking lights are generally available which expose the edges of the film and provide marks on the film which are visible after processing. In the cladding burst experiment one light will be used to register uniform time intervals and the other will turn on to indicate the onset of rapid heating and then turn off at the moment cladding rupture is detected.

Typical films used for high-speed photography are sensitive to illumination over the spectral range of 300 nm to 650 nm. Illumination at wavelengths greater than 650 nm is not utilized by the film but can interfere with temperature measurement. The temperature measurement concept proposed for this system does not require the use of wavelengths shorter than 800 nm. It is therefore possible to optically isolate the pyrometers from the cinematography light sources by filtering the incident light to remove all energy at wavelengths greater than 800 nm. The best lamp source should have as little energy in the red end of the visible spectrum as possible. Xenon arcs are not the optimum lamp choice since more than 50% of their energy is in the infrared. Mercury arcs have a much better energy distribution and would be preferred but factors such as cost, simplicity and uniformity of lighting led to the choice of tungsten halogen projector lamps. Four of these lamps, positioned to direct light at the fuel rod from equally spaced positions around the axis of the fuel rod, assure uniform illumination. Direct lighting at 45° from the chamber axis helps to accentuate features such as scratches or surface irregularities and produces no specular glare in the direction of the cinematography optics. Light is trapped within the chamber because of the use of highly reflective inner surfaces. This enhances illumination of the sample as illustrated by the following considerations. If P watts of light enter the chamber, then the energy available after the first reflection is PR where R is the reflectivity of the surface. Assuming uniform energy distribution, a condition only approximately achieved, the scattered energy incident upon any surface of unit area within the chamber is PR/A where A is the surface area of the chamber. As time progresses each reflection adds to the total energy trapped so that the total energy incident upon any surface of unit area within the chamber is approximated by

$$F \cong (PR/A) (1 + R + R^2 + \dots) \quad (1)$$

i.e.,

$$F \cong \frac{P}{A} \left(\frac{R}{1-R} \right) \text{ watts/cm}^2. \quad (2)$$

Typical photographic films require about 0.1 erg/cm² for an exposure to an optical density of 1 above gross fog.^{1,2} Using the required exposure of 0.1 erg/cm² and an exposure time of 1/25,000 second (which is the approximate exposure at 10,000 frames/sec), the required power density, F_2 at the film is 2.5×10^{-4} watt/cm².

In order to image the 2.5-inch long fuel rod on a 16-mm frame (major dimension 0.4 inch) the magnification must be 0.16X. This implies a required power density, F_1 , at the fuel rod surface given by

$$F_1 = 2F_2 / (0.16)^2 = 0.02 \text{ watt/cm}^2 \quad (3)$$

where the factor 2 is an allowance for losses in the optical path. Since the projected 6-inch diameter enclosure has about 1000 cm² of inside surface area, the optical power input must be (from Equation 1)

$$P = \frac{FA}{R} (1-R) = 9 \text{ watts} \quad (4)$$

for reflectivity (R) of 0.7.

It is estimated that a single 300-watt tungsten halogen lamp with dichroic reflector will generate 30 watts of effective optical power (i.e., optical power useful for film exposure). Even if only 25% of this energy gets into the enclosure, one lamp would provide most of the required energy. However for uniform illumination three or more lamps should be used. The spectral distribution of energy from a tungsten halogen lamp is shown in Figure 4. The lamp output as modified by a dichroic reflector and an 80-mm water filter is also shown and still contains unwanted energy in the 0.8 to 1.2 micron region which can be eliminated by use of a spectrally selective filter.

Figure 4. Spectral characteristics of tungsten halogen lamp.

Photographs were recorded using four projector lamps aimed at the sample from above the chamber. The diffuse, reflective chamber interior and the distributed light sources resulted in an acceptable illumination pattern on the sample. No severe hot spots were noted and the image density was well within the range of panatomic film which was used for this test.

Light emitted by the fuel rod because of its incandescence at 1100°C has a power density of less than 0.0016 W/cm² in the spectral region from 300 nm to 650 nm. This is less than 10% of the film exposure effective optical intensity in the chamber created by the halogen lamps. Therefore the fuel rod incandescence will have essentially no effect upon film exposure. The sample radiance will be even less of a factor during most of the tests as it is significantly smaller at temperatures below the upper test value of 1100°C.

Pyrometry

Infrared temperature measurements can be made by focusing the energy emitted by a region of the fuel rod surface upon a suitable detector. The signal provided by the detector is a measure of the temperature. The detectors projected for this system are a silicon photovoltaic cell and a lead sulphide (PbS) photoconductive cell whose responsivities peak at 0.9 μm and 2.3 μm, respectively.² These two detectors were chosen because they have sufficient detectivity to cover the range from 500°C to 1100°C. The silicon detector operates well into the short wavelength end of the radiance spectrum of the fuel rod. This decreases the dependence upon an accurate knowledge of the emissivity of the fuel element surface for accurate temperature measurement. PbS is used as a second detector for the purpose of obtaining a ratio temperature independent of absolute values of the emissivity. The spectral response characteristics of these two detectors allow the use of readily available optical crown glass lenses for imaging.

The interior surface of the chamber provides high reflectance in the infrared spectrum selected for the pyrometer (0.8 to 3.0 microns). This will increase the effective emissivity of the sample and reduce errors that can occur in the temperature calculations. An optical block diagram of the pyrometry system is shown in Figure 5. For a 1-second transient test an analog recording of the temperature sensors output is feasible. The three analog signals correspond to the output of the silicon and PbS detectors and the ratio of these outputs. Crown glass lenses and gold mirrors are utilized in the periscope and are stock items of modest cost. Ninety degree bends occur in the periscope at the mirror locations although they are not indicated in Figure 5. Accuracies of ±20°C at 1100°C are feasible but only if care is taken to compensate for the lack of precise knowledge of the emissivity.

Determination of the actual or true temperature T from a detector signal requires an accurate knowledge of the emissivity ε of the sample over spectral band to which the detector responds.³ If S is the temperature indicated by a pyrometer as a result of the

Figure 5. Block diagram of radiation pyrometer.

radiance of the sample in the spectral response band of the detector then the true temperature $T(^{\circ}\text{K})$ can be calculated from the expression⁴

$$\frac{1}{T} = \frac{1}{S} + \frac{\lambda}{C} \ln \epsilon \quad (5)$$

where λ is the operating wavelength and $C = 1.44 \times 10^4$ micron $^{\circ}\text{K}$. Thus an accurate knowledge of the emissivity can be used to calculate the true temperature even for samples with ϵ less than unity.

Since emissivity values will probably not be known accurately, two forms of compensation for this uncertainty are suggested. These will be referred to as:

- 1) short wavelength pyrometry
- 2) ratio pyrometry.

Short wavelength pyrometry

The effect of uncertainty in the knowledge of the true value of the emissivity on the determination of the true temperature T can be assessed by using Equation 5 to find a value for the error in temperature, dT , caused by an uncertainty in emissivity, $d\epsilon$. The resulting equation is

$$dT = - \frac{\lambda T^2}{C} \frac{d\epsilon}{\epsilon} \quad (6)$$

In order to determine the true temperature T to within $\pm 20^{\circ}\text{C}$ at 1100°C (1373°K) for $\lambda = 0.9 \mu\text{m}$ the uncertainty in emissivity must be such that $d\epsilon/\epsilon \leq 0.17$. Note, however, that the magnitude of the error dT is directly dependent upon the effective wavelength λ which for a silicon detector is $0.9 \mu\text{m}$. If a PbS detector had been used the effective wavelength would have been about $2.3 \mu\text{m}$ and the resulting magnitude of the error dT would have been 50°K . This illustrates the advantage of operating at as short a wavelength as possible. The choice of a silicon detector was made with this consideration in mind.

Ratio pyrometry

A PbS detector is used in addition to the silicon detector to obtain the ratio temperatures, $R[^{\circ}\text{K}]$. The equation equivalent to Equation 5 but modified to apply to ratio pyrometry is

$$\frac{1}{T} = \frac{1}{R} + \frac{\ln(\epsilon_s/\epsilon_l)}{C(\frac{1}{\lambda_s} - \frac{1}{\lambda_l})} \quad (7)$$

where the subscripts designate the short (0.9 μm for silicon) and long (2.3 μm for PbS) wavelengths for the two detectors. The temperature error will now depend on the accuracy to which the ratio of emissivities is known. In order to determine the true temperature with an error of less than 20°C at 1100°C the error in specifying the ratio of emissivities must be less than 10%. Determination of the ratio of emissivities to this accuracy is at least as difficult as determining ϵ_s to within 17%. Thus ratio pyrometry should not be relied upon by itself but should be used in conjunction with separate measurements of temperature by the silicon and PbS detectors. Use of these data and the careful assessment of the normal spectral emissivity of the material used in the test samples should achieve the objective of $\pm 20^\circ\text{C}$ accuracy in temperature determination.

Extensometer

The gauging of fuel pin diameter changes in this experiment is based upon the use of an optical relay system to form an image of the fuel cladding on linear diode arrays located outside the hot cell as illustrated in Figure 6. The relay system consists of a low power periscope to form an image outside the hot cell and a set of magnification optics to form a second image of each edge of the fuel pin on separate linear diode arrays. The magnification optics operate at 1X magnification to cover the 50% strain range and at 11X magnification to cover the 1% strain range. Satisfactory edge imaging can be performed with either an illuminated sample against a dark background or the converse. The diffuse chamber interior and the illumination provided for the cinematography will cause both the sample and the chamber interior to be fairly bright. It is therefore possible to view the bright sample against a dark background by placing an un-illuminated port behind the sample on the opposite side of the chamber.

Figure 6. Block diagram of extensometer.

In order to assure that chromatic aberration does not compromise the sharpness of the edge images a broad bandpass filter should be used to limit the energy seen by the diode arrays to the region between 600 nm and 700 nm. This is a compromise that allows the use of readily available visible spectrum optics and still maintains reasonable detector sensitivity (typical silicon behavior).

The accuracy of the determination of time-dependent strain is enhanced by curve fitting analysis of the recorded data to determine the constants of the equation

$$D(t) = D_0 + \left(\frac{dD}{dt}\right) t \quad (8)$$

$$= D_0 [1 + (\text{strain rate}) t] \quad (9)$$

where D and D_0 are the time dependent and initial values of the diameter, respectively. The high data rates for diode array systems are extremely useful for performing curve fitting analysis. For example with the 256 element, 10 MHz diode array system, more than 35,000 diameter values are obtained during a 1-second test interval.

Calculations have been performed to assess the effect of the digital nature of the array in a gauging application and to determine the number of diode elements that should be traversed during a test to achieve the accuracy of the calculated strain curve. Artificial data were generated using the equation for a straight line given in Equation 8. The data range was then broken into a number of equal size segments that represent the finite sized diode elements. The constants for a linear least squares fit were then calculated for a variety of segment sizes. The standard deviations for the coefficients were also calculated with the result that for an expansion covering 50 diode elements the strain rate error is expected to be less than 0.05% and the standard deviation of the coefficient is 0.06% of the actual value.

Summary

A conceptual design for an integrated high speed cinema, pyrometer, and extensometer system has been developed to monitor materials tests in a radiation hot cell environment. The system design provides a photographic record of the experiment at 10,000 frames/second over a 1-second test duration. The use of a reflective chamber interior improves illumination uniformity and reduces lighting power requirements for successful film exposure. The recommended pyrometer employs two-color detection and allows the use of ratio techniques for temperature calculation. An optical extensometer employing linear diode arrays monitors diameter changes during the test.

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