JUL 2 1965

SC-DC- 65 1507

CONF-654002-1

COMPARISON OF HEAT-FLUX SENSORS USING THERMAL RADIATION SOURCES

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ABSTRACT

An investigation of discrepancies observed in measurements of thermal flux rates from radiating graphites is reported. Simultaneous measurements were made using thermal flux sensors of three different designs. Similar measurements were made of thermal flux rates from quartz infra-red lamps.

Thermal flux sensors having 180° view angles without windows and 90° view angles with quartz windows were used in the investigation, the purpose being to examine the effects of possible emissivity changes on the unprotected sensors.

INTRODUCTION

Apparent discrepancies in measured thermal flux rates from radiating graphite sources in oxidizing atmospheres have dictated the need for an investigation to determine the cause of the discrepancies. The apparent differences were noted during a series of tests in which electrical power was programmed to the source and the thermal flux rate was sensed on water-cooled thin foil calorimeters in which the face of the calorimeter was directly exposed to the radiating source at a distance of one and one-half inches. This distance seemed sufficient to prevent convective transfer to the sensor.

The most simple approach to the problem appeared to be simultaneous measurement of thermal flux at a constant rate using sensors of different designs based on the two most common theories, the foil principle^{3,6} and the slug or slope principle.⁷ In order to examine the possibility of degradation of the emissive coating on the foil sensor, one slug or slope sensor with a quartz window and a 90° effective view angle was utilized.

Thermal measurement literature³ generally defines as "calorimeters" those instruments capable of measuring heat transmitted by radiative, convective, and conductive modes. "Radiometers" are generally defined as instruments sensitive only to radiated thermal flux.

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The arrangement of the sensors one and one-half inches horizontally from the source so that hot gas flow was vertical seems to preclude the possibility of convection heating of either sensor. Direct conduction heating of the sensors was prevented by adequate insulation covering all parts of the sensor except the face exposed to the thermal flux.

The eighteen different thermal sensors used for this investigation consisted of two basic designs of calorimeters and one basic design of radiometer. Figure 1 shows a simplified drawing of these instruments, which are discussed in more detail in the following paragraphs.

Calorimeters

The calorimeter shown in Figure 1^a is constructed on the Gardon gauge principle ^{3,6} in which a thin foil disk is attached at the disk periphery to the water-cooled heat sink. One sensor wire of thermocouple material is attached to the center of the foil disk. The other wire of the thermocouple pair is attached to the heat sink. This arrangement results in a differential thermocouple between the disk center and the heat sink, the emf of the thermocouple being proportional to the quantity of heat being absorbed by the disk. For a water-cooled calorimeter of proper design, a steady or rapidly changing thermal flux may be measured.

The other calorimeter used in these investigations consists of a copper slug or rod having one end exposed to the thermal flux as is shown in Figure 1^b. The sides of the rod are insulated or protected from heat by the outer sleeve. The theory of operation of this sensor⁷ is based on the concept of one dimensional heat flow through a thermal conductor. For a non-varying thermal input to the sensor, a straight line rate-of-rise is measured by the thermocouple attached to the "cold" end of the rod, within limits defined by the reference literature. This rate-of-rise is a function of the diffusivity and the length of the sensor rod and the emissivity of the surface receiving thermal flux. Emissivity of the receiving surface was 0.97.

Radiometer

The radiometer used for the tests consisted of a one-eighth-inch thick disk mounted behind a window of fused quartz as shown in Figure 1^c. The disk was supported by three needle points to limit heat conduction away from the disk by the mounting structure. The needle points are covered with an absorbing black, which receives thermal energy at the same rate as the sensing disk, maintaining a lower temperature difference

between the needle points and the sensing disk, further limiting conduction losses away from the sensing disk. The theory of operation of this sensor is similar to other slug-type sensors in that a measuring thermocouple of relatively fine wire is attached to the back of the disk or slug. The rate of change of temperature with respect to time is proportional to the thermal flux into the sensing disk. However, this sensor has a viewing angle of 90° and receives thermal flux through a quartz window. In comparing the measurements of a calorimeter having a 180° view angle with a radiometer of 90° view angle and a window, it is necessary to correct the radiometer for the attenuation of the window. The radiometer would then be expected to indicate a higher flux rate than the calorimeter⁸, because the radiator completely fills the view angle of the radiometer.

DISCUSSION OF COMPARATIVE RESULTS OF FLUX MEASUREMENTS FROM GRAPHITE BLOCK

Comparative results of the first seven tests using the graphite black source are plotted graphically in Figure 2. Corrections have been applied to the radiometers to account for the attenuation of the quartz window, losses due to re-radiation from the sensor slug and non-linearity of the thermocouple.

Calculation of the quartz window attenuation loss was done by plotting the grey body radiation curve for the graphite block at one temperature from the best available emissivity data.¹ The energy transmitted through the fused quartz window is plotted on the same graph. Transmission loss² through the quartz was obtained by comparison of areas under the two curves, the difference amounting to 15%. It was realized that corrections must be applied to account for transmissivity of the quartz window, and that data reduction would be time consuming. For this reason, only one curve for correction of the quartz transmission is presented, that being Figure 3, at a temperature of 3950°F .

Re-radiation losses from the sensor slug taken from literature on a similar device⁴ were assumed to be 0.9% per second.

Correction for non-linearity of the thermocouple (copper-constantan) amounted to a maximum of 7% on tests 1 and 2, Figure 2, to 3% on tests 4 and 5. No correction for non-linearity were made on tests number 6 and 7. The total correction to the radiometer readings of Figures 2 and 4 is added on above the short horizontal line.

Conduction losses from the radiometer sensing slug are considered to be negligible compared to other losses because of the short exposure time, the point contact mounting and the small thermocouple attached to the back of the sensor. Emissivity of the radiometers was 0.97.

The two water-cooled calorimeters used in the measurements shown in Figure 2 are commercially produced instruments with the sensing face coated with a proprietary black of known constant emissivity over a broad spectral range. The calorimeter is then compared with a "standard" calorimeter which

has been calibrated against a black body cavity whose temperature is determined by optical means traceable to the National Bureau of Standards. A curve of absorbed or incident flux rate vs. emf output of the calorimeter is supplied. The only other correction supplied is the designation of the receiver emissivity from which either the incident or absorbed flux could be obtained if the other were given. Emissivity of the calorimeters is listed as 0.89 on the calibration sheet supplied by the manufacturer.

The effect of adding loss corrections to the radiometer readings is noted from Figures 2 and 4, where the difference between the two instruments can now be attributed to the radiometer view angle.

In test 3 of Figure 2, addition of the loss corrections was sufficient to note the effect of the view angle differences between the calorimeters and radiometers.

Results from the non-cooled slug calorimeter, Figure 1^b, are plotted in Figure 2. Differences in reading between this calorimeter and the water-cooled foil calorimeter are sufficiently consistent in the first five tests to perform a recalibration using the water-cooled foil calorimeter as a "standard." No correction has been made for losses in this calorimeter. Loss corrections and calibration methods are described in the references 5 and 7, but the range of correction is not defined and time did not permit additional investigations to determine the effects.

DISCUSSION OF COMPARATIVE RESULTS OF FLUX RATE MEASUREMENTS FROM QUARTZ INFRARED LAMPS

Results of comparing eleven water-cooled calorimeters (Figure 1^a) produced and calibrated by the same manufacturer show closer agreement, Figure 5, than is noted in Figure 2. The calorimeters were of four different ranges, viz, 500, 120, 60 and 30 BTU/ft²-sec. Two tests were done at different flux rate levels using each pair of calorimeters. Observing test 1 of Figure 5, differences in calorimeter readings apparently resulted from differences in emissivity of the pair. The higher reading sensor had been re-coated with Parsons Optical Black which appears to have a higher emissivity than the coating received from the supplier. On the second test there is good agreement between sensors number 3 and 2 at the 75 BTU/ft²-sec. level but the disagreement seems to be non-linear at twice the flux rate.

The third test of the series compares a calorimeter of 120 BTU range, number 4, with the low reading sensor number 2 in the previous tests. A linear difference of six percent is noted. In the fourth test of the series a percentage difference is noted which may be the result of emissivity changes of the sensor faces.

In the fifth and sixth tests of the series, calorimeter number 4 compares favorably with two other sensors, numbers 6 and 7. This is sufficient evidence to suspect an undesirable non-linearity in the calorimeter number 2 (500 BTU range) when used at low levels. Sensors number 8 and 9 were tested immediately after receipt from the manufacturer. Good agreement is noted. The last test showed sensors of 30 BTU range to be in error as much as 19.6% after a period of use. This disagreement is difficult to explain on the basis of emissivity differences.

CONCLUSION

The effect of view angle differences between the readings of the calorimeters, Figure 2, and the corrected radiometer readings is most pronounced at the higher flux rates and consequent higher temperatures of the radiating source. By reference to a transmission curve² for quartz windows, it may be seen that the fused quartz attenuation is a function of the window thickness and wave length, increasing sharply past three microns. In order to correctly evaluate view angle effects at the lower energy levels shown in Figure 2, it appears necessary to plot curves of total energy transmitted through the sensor window at each temperature, as was done in Figure 3 at 3950°F. This will be done as time permits.

Data from the tests using graphite radiators is not sufficiently consistent to draw conclusions on the effect of emissivity change caused by use of the calorimeters without protection of the calorimeter faces. From a study of the references and from published literature of thermal sensor manufacturers, it appears that non-linearity of sensing material thermal constants, non-linearity of thermocouples and effects of re-radiation and conduction may be more pronounced than an emissivity error. It is noted that there is disagreement between several authors on the quantitative effects of conduction and re-radiation losses from slug calorimeters.

Measurements of flux rates from quartz infra-red lamps using water-cooled calorimeters shows linear errors in reading on tests number 1 and 4 and non-linearity in test number 2. These effects would lead to a conclusion that some means of sensor recalibration should be employed, as suggested by the instrument manufacturer. An alternate solution could be the use of radiometers with sapphire windows; however, the effects of view angle and attenuation of the window would have to be taken into account.

ACKNOWLEDGEMENT

The information presented in this paper resulted from the combined efforts of several Sandia Corporation personnel. These are R. L. Ault and T. M. Unkelhaeuser of the Radiant Heat Division, B. E. Bader of Dynamics Analysis Division and D. L. Krenz of Environmental Evaluation Division.

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FIGURE 1 a - WATER COOLED RAPID
RESPONSE CALORIMETER
180° FIELD OF VIEW

FIGURE 1 b - SLOPE OR SLUG
CALORIMETER BASED
ON ONE DIMENSIONAL
HEAT FLOW THEORY
NON-COOLED 180°
FIELD OF VIEW

FIGURE 1 c - NON-COOLED RAPID
RESPONSE RADIOMETER
90° FIELD OF VIEW

FIGURE 1 d - SLOPE OR SLUG
RADIOMETER NON-
COOLED 90° FIELD
OF VIEW

FLUX RATE IN BTU/FT²-SEC.

FIGURE 2. COMPARATIVE READINGS OF CALORIMETERS AND RADIOMETERS USING GRAPHITE SOURCE.

- (1) Emissivity factors obtained from data on page Volume I, Handbook of Thermophysical Properties of Solid Materials, by Goldsmith, Waterman and Hirschhorn.
- (2) Quartz transmission factors obtained from Figure 9.2 in The Detection and Measurement of Infra-Red Radiation, by Smith, Jones and Chasman.

FIGURE 3. SPECTRAL DISTRIBUTION FOR BLACK BODY, GRAPHITE RESISTOR AND QUARTZ-ATTENUATED GRAPHITE RESISTOR.

FIGURE 4. COMPARATIVE READINGS OF CALORIMETER AND RADIOMETER USING GRAPHITE SOURCE.

FIGURE 5. COMPARISON OF WATER-COOLED CALORIMETERS SENSING THE RADIATION FROM QUARTZ INFRA-RED LAMPS.