RADIATIVE CALIBRATION OF HEAT FLUX SENSORS AT NIST – AN OVERVIEW

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Rerinted from the ASME Heat Transfer Proceedings. Volume 3. HTD-Vol. 353. American Society of Mechanical Engineers (ASME). ASME International Mechanical Engineering Congress and Exposition. 1997,159-164 pp,1997.

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

HTD-Vol. 353, Proceedings of the ASME Heat Transfer Division
Volume 3
ASME 1997

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ABSTRACT

This paper describes the current capabilities and future plans at the National Institute of Standards and Technology (NIST) for radiative calibration of heat flux sensors. Experimental methods using an existing blackbody and high power lasers have been developed to characterize a reference electrical substitution radiometer and heat flux sensors, respectively. Tests carried out on a typical Schmidt-Boelter heat flux sensor showed long term repeatability of calibration within ± 0.4 %. Factors, such as purge gas flow, affecting sensor calibration when using high temperature blackbodies are discussed. To enhance the present capabilities, two additional blackbody setups are planned. These are a high temperature blackbody operating up to 3200 K with the possibility of calibrating sensors at power levels up to 200 kW/m^2, and a spherical blackbody with a water-cooled aperture to calibrate sensors in a low convection environment.

INTRODUCTION

Accurate heat flux measurements in practical applications such as fire research and convection heat transfer using heat flux sensors have been the most elusive. Large uncertainties are introduced frequently both during calibration and/or due to the application environment; total uncertainties of 5 % or higher in measurements are not uncommon. It is often difficult to quantify accurately the uncertainties accrued during calibration, and while transferring the calibration to actual measurements. Calibration methods used by sensor manufacturers frequently depend on derivation of heat flux from pyrometric temperature measurements traceable to NIST. However, due to different methods in use, calibration of the same sensors by different manufacturers or laboratories show variations as large as ±8 % (Sarkos et al., 1995). This is due to the fact that no traceable U.S. calibration national standards currently exist for heat flux measurements. Development of a traceable national standard will help to reduce the calibration-related uncertainties in measurements using heat flux sensors.

A recent workshop (Moffat and Dank, 1995) on heat flux transducer calibration addressed the need for establishing heat flux calibration standards to provide traceability to sensor manufactures and users, in particular for heat flux ranges up to 100 kW/m^2. One of the recommendations was to use the wide range of radiation facilities available at NIST, and also to address the requirement for new radiation facilities to meet the calibration needs of high heat flux sensors. The Optical Technology Division (OTD) at NIST has a number of facilities, including a cryogenic radiometer, high temperature blackbodies, and high power lasers, which are currently used to maintain and disseminate the radiance temperature scale. These facilities can be suitably adapted to provide high levels of irradiance required in heat flux sensor calibration. Two such facilities have been presently adapted for transfer calibration (Murthy and Tsai, 1997) of heat flux sensors: a Variable Temperature Blackbody for broadband transfer calibration of sensors from a reference radiometer, and an Argon/Krypton ion laser facility for spectral calibration of the reference radiometer. Two other facilities are under final stages of development. The first one uses a spherical blackbody similar to the technique developed by Olsson (1991). This facility is planned to be used in the development of an absolute calibration technique. The second facility employs a high temperature graphite tube blackbody BB3200pg (Sapritsky, 1996) developed at VNIIOFI[1]. This facility is expected to provide heat flux levels up to 200 kW/m^2 at the sensor surface.

[1] All Russian Research Institute for Optophysical Measurements, Moscow, Russian Federation.

The present paper gives a description of the OTD radiative calibration facilities in use and under development, and discusses their capabilities and limitations. Typical results from the calibration of heat flux sensors are presented along with a discussion of future plans towards developing NIST traceability for heat flux sensor calibration.

RADIATIVE CALIBRATION FACILITIES

Several fixed-point blackbodies and variable-temperature blackbodies suitable for broadband calibration of sensors are operational at OTD. In view of the high heat flux levels required at the sensor surface, it is necessary to use a wide aperture blackbody with variable temperature capability. A wide aperture results in higher radiation at a given temperature and better uniformity of heat flux distribution across the sensor surface. Variable temperature capability is useful for continuous change in heat flux level at a fixed value of the configuration factor between the blackbody aperture and the sensor surface.

High power laser sources are ideally suited for spectral characterization of cavity-type radiometers with reference to a radiometric standard or a transfer standard detector that has been calibrated in a primary facility like the High Accuracy Cryogenic Radiometer (Gentile et al., 1996). The following sections describe three blackbody facilities, and a laser facility suited for heat flux sensor calibrations traceable to a primary radiometric standard.

25-mm Variable Temperature Blackbody (VTBB)

Figure 1 shows the schematic layout of the 25-mm VTBB[2]. This is an electrically heated graphite tube cavity blackbody furnace. The heated tube cavity diameter is 25 mm, and the heated section is 28.2 cm long with a center 3 mm thick partition. Direct resistance heating of the tube using large AC currents and low voltages provides for quick heating and cool down of the furnace. The heated tube is insulated on the outside using layers of graphite felt and grafoil tape. The tube end caps are water cooled and are directly connected to the heating electrodes. The design provides a sharp temperature gradient between the water-cooled copper end cap and the graphite heater element. This helps in achieving a uniform temperature distribution along the length of the graphite tube. Different lengths of uncooled graphite extension tubes can be attached to both end caps.

The furnace temperature is computer controlled. An optical pyrometer measures the temperature by sensing radiation from one end of the furnace. Depending on the operating temperature range, different size apertures are fitted to the pyrometer to filter the radiation from the furnace. A PID controller regulates the power supply to maintain the furnace temperature to within ± 0.1 K of the set temperature. The maximum recommended operating temperature for the furnace is 2923 K. The heat flux sensors to be calibrated and the reference radiometer are located at a fixed distance ... exit of the blackbody.

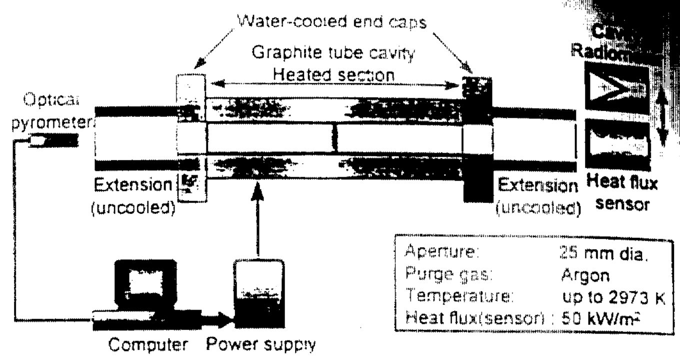

Fig. 1. Schematic layout of the 25-mm Variable Temperature Blackbody (VTBB).

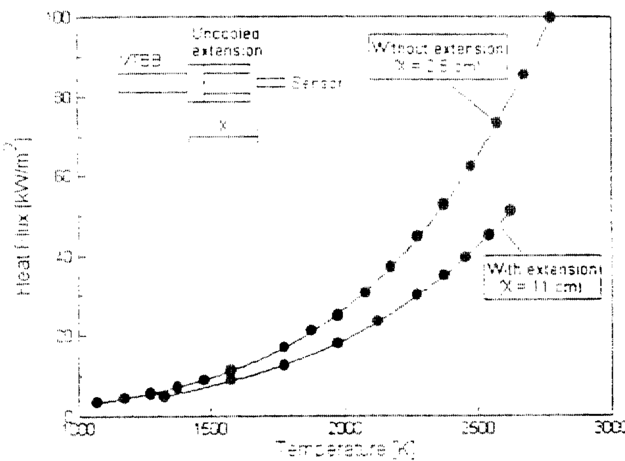

Fig. 2. Measured heat flux for two sensor positions from the blackbody aperture.

The apparent emissivity of the radiating aperture of the furnace is 0.99. The heat flux incident on the sensor surface depends on the location of the sensor from the effective blackbody aperture. Figure 2 shows the measured heat flux levels at two locations. At the location closest to the aperture (2.5 cm), it is possible to realize heat flux levels up to 100 kW/m^2. However, to locate the sensor at this position, the uncooled extension at the exit aperture of the cavity cannot be installed. Since the absence of the uncooled extension creates a non-uniform distribution of the argon purge gas flow in the cavity, resulting in reduced life of the graphite tube and end caps, this configuration is avoided. Tests have shown it is better to operate with a short extension, which does not significantly affect the performance of the radiating cavity. With this short extension, the sensor can be positioned at a distance of about 11 cm from the radiating aperture. The maximum

[2] Thermogage Inc., Frostburg, MD. Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

realizable heat flux at this location is approximately 50 - 60 kW/m^2.

High temperature blackbody (BB3200pg)

One of the major problems with high temperature graphite tube blackbodies is the temperature gradient along the cavity length. Several design improvements and the use of new materials such as pyrolytic graphite have made it possible to achieve high temperatures with highly uniform spectral radiance from the aperture. The BB3200pg blackbody developed at VNIIOFI can operate up to 3200 K , and has an apparent emissivity of 0.999. The OTD now has an operating BB3200pg blackbody intended for use in irradiance scale realization in the UV region. Figure 3 shows a schematic layout of the blackbody. The radiating cavity has a number of pyrolytic rings with inner and outer diameters of 40 mm and 50 mm, arranged to give a total cavity length of 230 mm. The pyrolytic graphite material is anisotropic, having high electrical resistance along the layers and high thermal conductivity across the layers, thus keeping the temperature variations within the cavity small. Preliminary checks have shown that it may be possible to achieve heat flux levels of up to 200 kW/m^2 at the sensor surface with this blackbody. It is planned to utilize this facility in the next phase of the heat flux sensor calibration program.

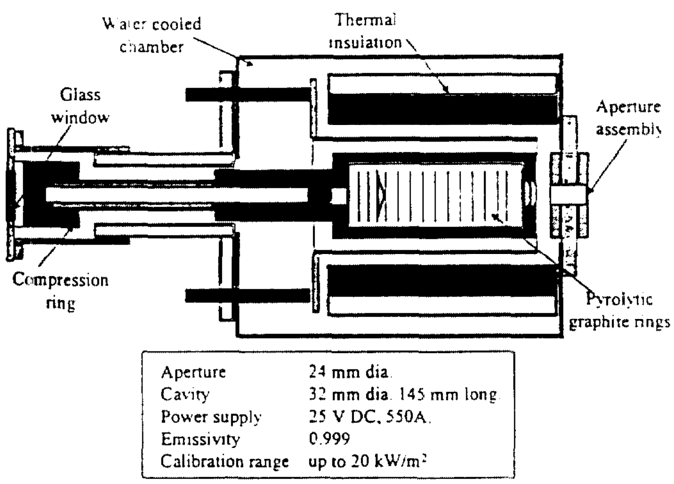

Fig. 3. Schematic layout of high temperature BB3200pg blackbody.

Spherical blackbody

The high temperature graphite tube blackbodies require continuous purging of the radiating cavity by an inert gas like argon to prevent sublimation of the cavity material. When the sensor is located close to the aperture, the exiting argon gas flow impinges on the sensor surface causing unsteady heat transfer from the sensor surface. This effect is in addition to the heat loss from the sensor surface due to free convection. To alleviate the effects of free convection, a study in Sweden (Olsson, 1991) used a spherical blackbody with an enclosed gage housing and aperture assembly. The heat flux at the sensor furnace was calculated considering the radiation balance within the enclosure. The method was presented as an absolute calibration technique, requiring only knowledge of the enclosure geometry and the aperture characteristics to determine the heat flux at the sensor surface. The technique of using a cooled-gage housing assembly provides a new approach to address the convection problem, often a disturbing factor in radiation calibration unless the measurements are done under vacuum conditions.

A parallel study has been initiated at OTD to study the beneficial effects of using the Swedish technique. A facility based on this approach has been designed, and is now ready for evaluation. Figure 4 shows a schematic layout of this facility manufactured by Mikron Instrument company. The blackbody cavity is a spherical furnace, 0.23 m diameter, and is fitted with a 50 mm diameter radiating aperture. The furnace walls are made of clay, and are electrically heated. The furnace inner surface is coated with a high temperature black paint with a maximum operating temperature of 1373 K for continuous use. Operation at higher temperatures up to 1446 K is possible for short duration. The cavity temperature is measured by a precision type S thermocouple. A PID controller maintains the cavity temperature at a set value within 1 K. Provision for computer control of the temperature is available through a serial RS-422 interface.

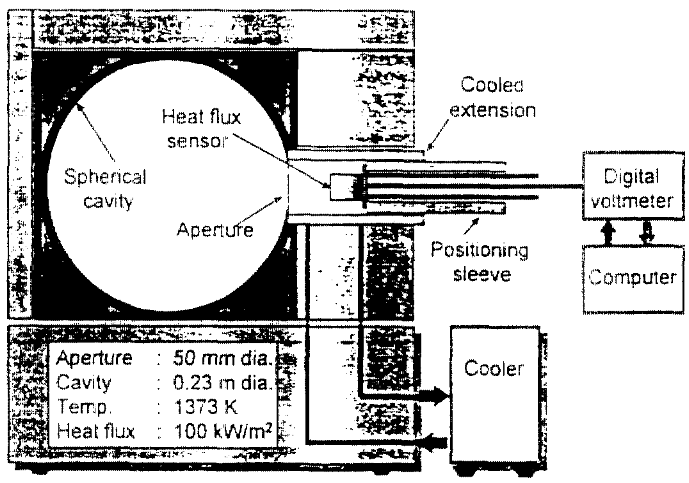

Fig. 4. Schematic layout of spherical blackbody with cooled aperture.

A salient feature of this facility is a single-piece, water-cooled extension tube with a precision aperture at one end. The other end serves as an opening for inserting the sensor housing assembly. The cooled extension tube minimizes effects of reflected radiation from the inner surface of the tube onto the sensor surface. Circulating refrigerated water cools the extension tube and the aperture. A stop ring on the inner surface at a distance of 12 mm from the aperture end helps to precisely locate the sensor assembly inside the tube. Four type K thermocouples are located 90° apart on the inner surface of the tube, midway between the aperture and the stop ring.

Figure 5 shows the proposed assembly for mounting and locating a typical 25-mm diameter Gardon gage inside the blackbody extension. This assembly has a positioning sleeve which slides in the extension tube up to the stop ring location.

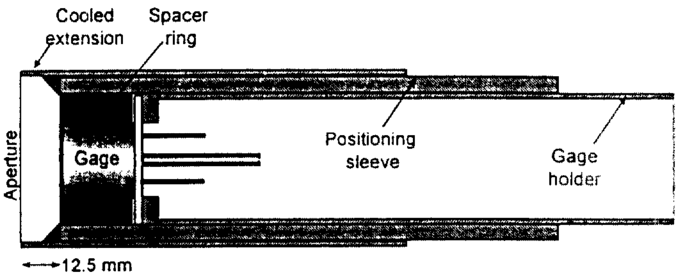

Fig. 5. Water cooled extension and gage housing for the spherical blackbody.

The positioning sleeve is slotted to prevent fouling with the surface-mounted thermocouple lead wires. The gage holder assembly is inserted into the positioning sleeve. Other types of gages, up to a maximum diameter of 25 mm can be attached to the gage holder using a suitable adapter. By using different size spacer blocks, the gage can be located at known distances from the radiating aperture. With the present design and location of the sensor, it is expected that heat flux sensors can be calibrated up to 100 kW/m^2, at a maximum temperature of approximately 1373 K.

<u>High Power Laser Facility</u>

The power range of primary radiometric standards are small (≈ 1 mW). The power range of cavity-type radiometers used in heat flux sensor calibration is several orders of magnitude larger than that for the primary standards. The high power laser facility, shown schematically in Fig. 6, is used for transferring the calibration from the primary standard to the full range of the radiometer. The system is comprised of two high power ion lasers, argon and krypton, lasing at 647.1 nm and 514 nm, respectively. The laser beam, after being defined by suitable apertures passes through a beamsplitter. The main beam output is measured by the primary standard or the radiometer to be calibrated. The beamsplitter reflects a portion of the beam (≈ 8 %) into an integrating sphere. The power of the reflected beam is monitored by a silicon detector mounted on the integrating sphere. The silicon detector serves as an intermediate transfer detector.

First, the silicon detector is calibrated with respect to the primary standard by operating the laser at low powers within the power range of the primary standard. Next, with the radiometer aligned in the path of the main beam, the laser is operated at higher powers. The output of the silicon detector and the radiometer are compared for different power levels within the range of the radiometer. Using the calibration obtained in the first step, the silicon detector output is converted to power level of the main beam entering the radiometer. The radiometers characterized using this facility are used with blackbodies described earlier to calibrate the sensors.

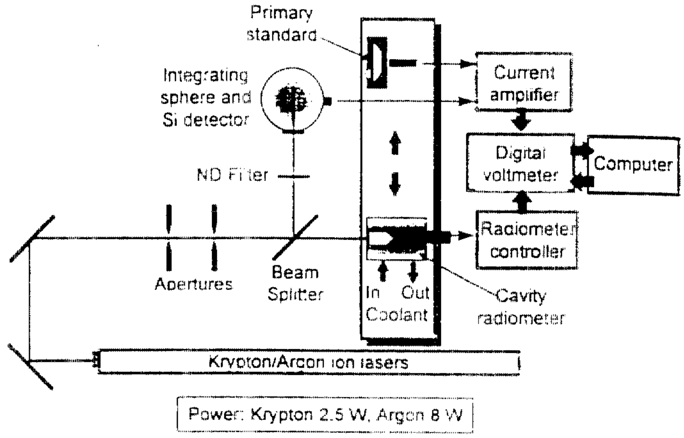

Fig. 6. Schematic layout of high power laser facility for cavity radiometer calibration.

RADIOMETRIC STANDARDS FOR HEAT FLUX

The heat flux sensors are calibrated for the incident heat flux using the blackbody facilities described. The incident heat flux at the sensor location is measured by a cavity-type radiometer. OTD presently uses a 42 kW/m^2 range Electrical Substitution Radiometer (ESR) which works on the principle of equivalence between thermodynamic heating and electrical heating. Generally, the ESR measurements are considered absolute, and are accurate to about 1 % when operating at ambient temperatures. Sources of error in ESR measurements are non-equivalence of the two heating modes, lead heating, and non-spectral flatness. To account for these effects and to keep track of the long term stability of the ESR, it is desirable to calibrate the ESR at regular intervals with respect to a primary standard, like a quantum efficiency detector (Zalewski, 1983), or a transfer detector with traceable calibration. The uncertainty associated with the primary standard is small, about 0.2 %, compared to other inaccuracies in heat flux sensor calibration.

RESULTS AND DISCUSSION

While developing new facilities and techniques, the existing facilities (VTBB and Laser facility) have been successfully adapted to calibrate sensors up to 50 kW/m^2. The sensors are calibrated with reference to an ESR previously calibrated against a primary standard. This technique, generally referred to as 'transfer calibration', is described in detail by Murthy and Tsai (1997). In the past two years, several Schmidt-Boelter type gages have been calibrated using the transfer calibration technique. These calibrations, while serving the immediate needs, were helpful in planning for the development of new facilities.

One of the requirements in developing traceable calibrations is to establish long term repeatability of the technique employed. Also, it is necessary to assess the effect of extraneous experimental factors on the gage calibration. The long term repeatability of the measurements in the VTBB was checked by calibrating a Schmidt-Boelter gage against the ESR at frequent intervals. In the past year, four sets of calibrations have been done. These calibrations included measurements of the sensor at different locations with respect to the blackbody aperture, and also over different blackbody temperature ranges. Further, after the first two sets of calibrations, the blackbody setup was modified to improve temperature uniformity along the radiating cavity.

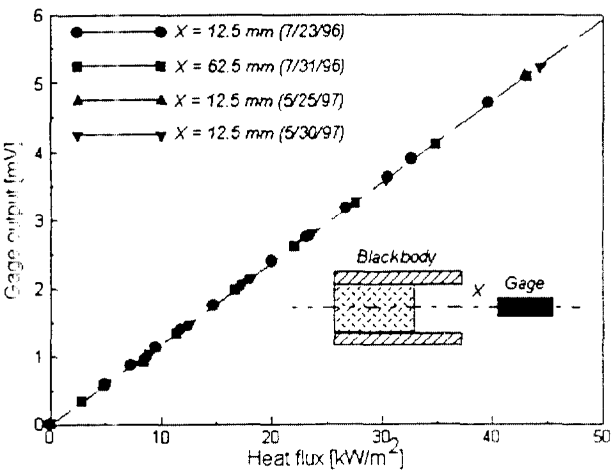

Fig. 7. Results of repeat calibrations of a Schmidt-Boelter gage in the 25-mm VTBB.

Figure 7 shows the measured gage output in mV for different levels of incident heat flux in the range 0 - 50 kW/m^2. All the four calibrations showed the expected linear response of the gage, with regression factors of unity. Table 1 gives the gage responsivity obtained from linear regression to the calibration data. The agreement in responsivity is within approximately $\pm$ 0.4 % of the mean value from the four calibrations. The good repeatability of the data supports the long term stability of the transfer standard ESR, Schmidt-Boelter gage, and the OTD test technique using the VTBB.

The transfer calibration technique has certain advantages. It is based on direct measure of the heat flux, rather than blackbody temperature measurements. Hence, any departure from the blackbody radiation due to extraneous experimental factors will have similar effects on both the reference radiometer and the sensor, and the calibration is not affected. Further, it is possible to monitor the long term stability of the reference radiometer by independent calibrations in the laser facility.

Table I: Measured responsivity of a Schmidt-Boelter heat flux sensor.

Test No.	X mm	Responsivity $mV/kW.m^{-2}$	Deviation from mean, %
1	12.5	0.1189	0.23
2	62.5	0.1184	-0.18
3	12.5	0.1190	0.38
4	12.5	0.1181	-0.43
Mean responsivity		0.1186	0.00
Std. Deviation		0.0004	0.37
Std. Error		0.0002	0.19

When using high temperature graphite blackbodies for heat flux sensor calibration, argon gas flow used for purging the cavity is a source of concern. The flow rate is small, less than 8 x 10^{-5} m^3/s, but due to the unsteady nature of the jet flow impinging on the sensor surface, the signal output requires averaging over a representative time scale. The fluctuations in output are about 1 % from the mean value at lower heat flux levels ($\approx$ 10 kW/m^2), and reduce to about 0.2 % at higher heat flux levels ($\approx$ 40 kW/m^2). The response time of typical Schmidt-Boelter sensors is about 50 ms, considerably smaller than the time constant of the reference ESR. Hence, the argon jet flow effects will be more significant on the sensor measurements. When the sensors are not water cooled, it is necessary to limit the exposure time to blackbody radiation to avoid overheating the body. Based on these considerations, averaging times of 10 s to 60 s are used for sensors.

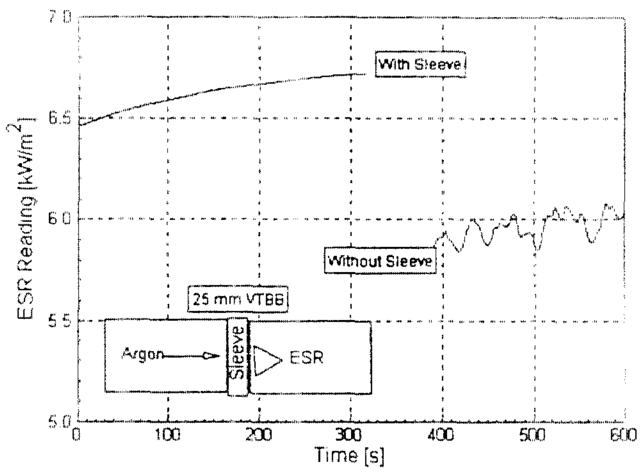

Fig. 8. Purge gas flow effects on heat flux measured by the ESR.

The ESR has a 1/e time constant of about 6 s. A time delay of about 60 s is allowed before the measurements are made. Since the ESR is water cooled, exposure time to blackbody radiation is not restricted. Hence, the ESR output was recorded over a period of several minutes to study the effect of argon gas jet flow. The measurements were made at a low heat flux level of about 6 kW/m^2. The results of this experiment, shown in Fig. 8, has two parts, corresponding to situations of normal exit jet flow, and with the flow blocked. The jet flow was blocked by inserting a spacer block between the ESR and the blackbody exit. With the normal jet flow, despite the long time constant, the output of the ESR is unsteady with a slow increase in the mean value. The gradual increase in the mean value is probably due to radiation from the heating of the graphite extension, which is not cooled. However, with the exit flow blocked, the unsteadiness in the ESR output is almost absent. This experiment suggests that the unsteady flow effects of the purge gas flow can be significantly reduced by confining the jet. With cooling, the effects of heating of the graphite extension on the sensor signal can be minimized. This scheme has been incorporated in the spherical blackbody design discussed earlier. It must be noted that the results shown in Fig. 8 are taken under conditions when the jet flow effects are dominant, and for a measurement duration much longer than the normal calibration test conditions.

The calibrations of various sensors with the present setup show that the total uncertainty in the calibration due to all known sources is approximately 1.5 % with a coverage factor of 2. A comparison of the calibration constants for various sensors tested at NIST with the manufacturer's calibration have shown differences in the range of 3 % to 5%. This may be due to the fact that different calibration methods are employed by the manufacturers. The present research program on heat flux sensor calibration in progress at OTD aims to reduce or resolve these differences by developing traceable heat flux standards.

CONCLUSIONS AND FUTURE PLANS

An existing high temperature blackbody (VTBB) and high power lasers have been adapted to perform heat flux sensor calibration up to 50 kW/m^2. Tests on a Schmidt-Boelter gage in the past year have shown repeatability of the calibration within ±0.4 %. It is planned to extend the capability to calibrate sensors up to 200 kW/m^2 using the new high temperature blackbody (BB3200pg). The proposed spherical blackbody will provide an opportunity to calibrate the sensors with different methods. By calibrating the same sensors in these facilities, it is hoped to make comparative assessment of the capabilities of different methods of calibration.

ACKNOWLEDGMENTS

The authors wish to acknowledge William Grosshandler and Ken Steckler from the Building and Fire Research Laboratory, and Steven Brown from the Physics Laboratory at NIST for useful discussions.

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