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Dual Active Surface Heat Flux Gage Probe

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DUAL ACTIVE SURFACE HEAT FLUX GAGE PROBE

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ABSTRACT

A unique plug-type heat flux gage probe was tested in the NASA Ames Research Center 2 × 9 turbulent flow duct facility. The probe was fabricated by welding a miniature dual active surface heat flux gage body to the end of a hollow metal cylindrical bolt containing a metal inner tube. Cooling air flows through the inner tube, impinges onto the back of the gage body and then flows out through the annulus formed between the inner tube and the hollow bolt wall. Heat flux was generated in the duct facility with a Huels arc heater. The duct had a rectangular cross section and one wall was fabricated from 2.54 cm thick rigid surface thermal insulation material mounted onto an aluminum plate. To measure heat flux, the probe was inserted through the plate and insulating materials with the front of the gage located flush with the hot gas-side insulation surface. Absorbed heat fluxes measured with the probe were compared with absorbed heat fluxes measured with six water-cooled reference calorimeters. These calorimeters were located in a water-cooled metal duct wall which was located across from the probe position. Correspondence of transient and steady heat fluxes measured with the reference calorimeters and heat flux gage probe was generally within a satisfactory ±10 percent. This good correspondence was achieved even though the much cooler probe caused a large surface temperature disruption of 1000K between the metal gage and the insulation. However, this temperature disruption did not seriously effect the accuracy of the heat flux measurement. A current application for dual active surface heat flux gages is for transient and steady absorbed heat flux, surface temperature and heat transfer coefficient measurements on the surface of an oxidizer turbine inlet deflector operating in a space shuttle test bed engine.

INTRODUCTION

The first goal of this research is to investigate the durability of a unique dual active surface heat flux gage probe operating in a hot and hostile environment. A second objective is to experimentally study heat flux measurement error caused by surface temperature disruptions arising from sensor intrusiveness. The prototype probe consists of a miniature convection cooled metal plug-type heat flux gage (ref. 1) welded to the end of a hollow metal bolt. A small tube is located inside the hollow bolt. Cooling air flows through the inner tube and impinges on a platform welded to the end of the bolt. The platform, in turn, contacts the rear of the thermoplug which is electrical discharge machined (EDM'ed) within the gage body. After impinging on the platform, the cooling air exits through the annulus passage formed between the tube and the bolt wall.

The dual active surface heat flux gage probe concept described herein is based on the design of the gages described in references 1 to 3. These gages were invented for direct sensor fabrication into metal materials with thicknesses of at least 0.127 cm (ref. 1). The probe concept extends the applicability of these gages to surface heat flux measurements on cooled walls having thicknesses less than 0.127 cm and also to surface measurements on nonmetallic material walls where direct sensor fabrication is not practical. For instance, the ceramic thermal barrier coated or uncoated metal walls comprising the cooling passages in ground based and aircraft gas turbine engines can be very thin. However, the miniature probe may be inserted through adjacent ribs or lands and positioned closely adjacent to and flush with the gas-side passage surfaces. In addition, by adjusting coolant flow through the probe, the surface temperature of the cooled gage body may be adjusted to closely match the surrounding wall temperature. This can minimize the heat flux measurement error resulting from thermal disruption caused by placement of the gage within the wall (ref. 4).

The Ames Research Center 2 × 9 turbulent flow arc-jet duct, which is part of the Arc-Jet Complex described in reference 5, provides a fine facility for developing transient and steady heat flux measurement methods. Mach numbers of 3.5, temperatures to 1800 K and heat fluxes to about 1 MW/m^2 are generated in this facility. Assessment of probe durability and heat flux measurement quality were investigated at transient and steady-state absorbed heat flux conditions ranging from 0.3 to 1.0 MW/m^2.

ANALYSIS

A photograph of the heat flux gage probe is shown in figure 1. A schematic drawing of the probe assembly is presented in figure 2. As shown in figure 2, cooling air flows through the probe inner tube and then impinges onto the back surface of the platform. The platform is welded to a gage which contains a post (figs. 3 and 4) which is EDM'ed into Inconel alloy 718 material. The post has a cylindrical shape and is surrounded by an annulus (figs. 3 and 4) which is filled with quiescent air. Air is a good thermal insulator. The post is integral with the gage wall which forms the front surface. Heat enters through this front surface and leaves through the back surface of the platform which is impingement cooled. Post temperatures are measured with thermocouples.

Heat is defined as energy in transit. It is possible to quantify this concept of heat in terms of appropriate heat flux and heat balance rate equations associated with temperature gradients and temperature changes instantaneously measured on the thermoplug residing within the gage. Conceptually, the total length of the thermoplug includes the wall thickness, the post length and the platform thickness (fig. 4). Because the post is thermally insulated on its side, it is assumed that there is one-dimensional heat transfer in the thermoplug. Instantaneous one-dimensional heat conduction in the thermoplug is shown conceptually in figure 5. The direction from the front surface to the back surface of the thermoplug is considered positive.

Temperature Changes (Heat Storage)

As the local temperature of the thermoplug material changes with time, the corresponding transient heat flux (ref. 2) is

$$\dot{q}_{store} = \int_0^L \left[\rho c_p \frac{\partial T}{\partial \theta} \right] dZ, \text{W/m}^2 \tag{1}$$

In equation (1), $\dot{q}_{store}$ is heat flux associated with heat storage, ρ and c_p are temperature variant density and specific heat of the thermoplug material, T is internal gauge thermoplug temperature, θ is time, L is the thermoplug length measured from the front active surface to the back active surface and Z is a distance measured along the axis of the thermoplug.

Temperature Gradients (Fourier's Law)

At any selected time, Fourier's law applied at the rear of the thermoplug is (ref. 2)

$$\dot{q}_{back} = -k\left(\frac{\partial T}{\partial Z}\right)_{Z=L}, \mathrm{W/m^2} \tag{2}$$

where k is the temperature variant thermal conductivity. This relationship applies to both steady-state and transient conditions.

Heat Balance

A conservation of energy equation describing the transient and steady heat balance on the thermoplug front surface is

$$\dot{q}_{front} = \dot{q}_{store} + \dot{q}_{back}, \mathrm{W/m^2} \tag{3}$$

Substituting equations (1) and (2) into equation (3) produces a heat flux equation for the thermoplug

$$\dot{q}_{front} = \int_0^L \left[\rho c_p \frac{\partial T}{\partial \theta}\right] dZ + k\left(\frac{\partial T}{\partial Z}\right)_{Z=L}, \mathrm{W/m^2} \tag{4}$$

where the temperature gradient is a negative quantity when heat is leaving the thermoplug.

To evaluate the partial derivatives of temperature versus time and of temperature versus distance given in equation (4), four least squares curve fit models are applied to the time variant and space variant temperature data obtained at the three temperature measurement locations on the thermoplug (fig. 4). These models describe linear and nonlinear parabolic, exponential and power equations.

Linear curve fits are used when equation (4) is a linear equation. Equation (4) is linear when the properties are constant. That is when, within experimental error, the properties do not vary with temperature along the thermoplug length. Nonlinear curve fits are used when equation (4) is nonlinear. Equation (4) is nonlinear when any one of the properties varies significantly with temperature along the thermoplug length. Properties are obtained from reference 6.

Correlation coefficients for each of the four curve-fit models are also computed. The correlation coefficient measures the goodness of fit of the equations to the data. The best-fitting curve is associated with the largest value of correlation coefficient. For best results, correlation coefficient values should be greater than 0.95. The equations of the best fitting curves of temperature versus time or temperature versus distance are differentiated and evaluated at desired times and locations. A discussion of how the derivative values are used in numerical methods for obtaining heat flux with equation (4) is presented in reference 2.

FABRICATION OF MINIATURE DUAL ACTIVE SURFACE HEAT FLUX GAGE PROBE ASSEMBLY

Probe Assembly

Figures 1 and 2 show the probe assembly. The assembly was comprised of a dual active surface heat flux gage body welded to the bottom of a hollow metal stem. A small tube was positioned inside the hollow stem at a distance from the bottom of the platform of 1.2 times the tube diameter. Cooling air enters through the inner tube (fig. 2) and then impinges onto the platform. The platform solidly contacts and was spot-welded to the rear of the post. After impinging on the platform, the cooling air exits through the annulus passage (fig. 2) and then out through the top of the stem.

Stem

The stem was fabricated separately from the gage body. The stem was machined from a stainless steel bolt. The head of the bolt was cut off and a hole was machined along the axis of the cylindrical bolt. The hole was not machined completely through the bolt length. The material remaining at the bottom of the hole serves as a flat-faced platform at the bottom of the bolt hole. Three grooves were electrical discharge machined (EDM'ed) along the outside surface of the bolt. These grooves extend along the length of the bolt. Thermocouple cables are buried in these grooves.

Gage Body

The gage body was EDM'ed from a solid piece of Inconel alloy 718. The body consisted of a cylindrical post surrounded by a concentric annulus. The annulus was EDMed only partially through the specimen. The EDM technique for simultaneously machining the post (plug) and annulus into the material is described in references 1 and 2. Figure 3 shows placement of the three thermocouples prior to welding the body to the stem. Figure 4 shows a cross-sectional side view of the stem welded to the post and to the edge of the gage body.

Thermocouple Fabrication

The three type K (Chromel-Alumel) thermocouples were fabricated from six commercial, single conductor swaged thermocouple cables each of which had a diameter of 0.0254 cm. After the cable was cut from the same spool, a length of one centimeter of sheath and ceramic insulation surrounding the thermoelement wire (diameter = 0.0038 cm) was stripped from both ends to expose the wire. To provide electrical insulation, any ceramic powdered insulation remaining after stripping was not cleaned from the wire. After stripping, the cable was heated to about 400K for several hours to drive out moisture inside the cable. Then the ends of the cable were sealed with a high temperature ceramic material. Note that no splices were made along the cable length. In preparation for spot-welding to the post, the thin coating of impurities formed on the post during the EDMing process was removed by fine-grit blasting. The exposed thermoelement wires were also fine-grit blasted to remove oxide coatings. Fine-grit blasting prior to welding is very important because the thermoelement wires will not strongly weld to the post when these coatings are present.

Thermocouple Installation into Gage Body

Three Chromel-Alumel thermocouples numbered 1 to 3 (fig. 4) were tack-welded to the post at distances of 0.046, 0.089 and 0.135 cm measured from the front active surface of the gage. The thermocouples were equally spaced around the circumferential surface of the post (fig. 3). A microscope equipped with an illuminator and an in-focus, zoom magnifier (50X) was used during the thermocouple installation. The cable was firmly strapped into the three slots machined into the back of the gage body (fig. 3). The straps are welded to the bottom of the slots, but not to the cable sheath. The cable must be firmly strapped so that it will not twist or rotate under the strapping material. After the cables are in place, the thermoelement wires are positioned in the annulus such that the ends of the two wires comprising each thermocouple pair are located close to the intended position for welding to the post. First, one thermoelement wire was welded to the post. Then the second thermoelement wire forming the thermocouple pair was welded next to (not on top of) the first wire. All thermocouple pairs were installed in this manner.

After the thermocouples were installed into the gage body, a fixture was designed to hold the gage body to the stem during the welding procedure. However before welding, the thermocouple cables exiting from under the platform were positioned and strapped into the three slots EDM'ed along the length of the bolt used to fabricate the stem. These cables extend from the bottom of the stem and along the entire length of the stem. As shown in figure 1, the cable then extends from the top of the stem to thermocouple plugs. After the cable was fastened into the grooves EDM'ed along the length of the stem, the heat flux gage body was welded to the stem. Then the welding fixture was removed.

APPARATUS

A variety of aerothermodynamic heating arc jet facilities are located at NASA Ames Research Center (ref. 5). The characteristics and durability of the miniature dual active surface heat flux gage probe shown in figures 1 to 4 were investigated in one of these facilities designated as the 2 × 9 turbulent flow duct facility shown in figure 6. Usually this facility is used for evaluating the performance of thermal protection system materials such as the rigid surface insulation tiles used on the Space Shuttle Orbiter. In this facility, air flows progressively through a Huels arc heater, a swirl chamber, a hollow electrode, a water cooled diverging duct comprising a semielliptic nozzle and a rectangular cross section and then out through a diffuser into a low pressure reservoir. The air is introduced tangentially into the swirl chamber and the resulting strong vortex motion is largely responsible for stabilizing the arc in the electrode region. The flow is choked at the nozzle throat and expands supersonically into the rectangular cross section. High enthalpy air generated by the arc heater flows through the water-cooled duct. The contoured shape of the duct is designed for well developed supersonic turbulent flow in the instrumented test section.

During ramp to steady facility operating conditions, hot turbulent air flows within the duct at surface pressures of 2000 to 14 000 Pa. Absorbed surface heat fluxes of 0.02 to about 1 MW/m^2 are generated in this facility. The Mach number at steady facility operating conditions is 3.5. Six water cooled Gardon heat flux gage reference calorimeters and three pressure taps were used to measure absorbed heat flux and wall pressure on one vertical side of the water cooled duct (fig. 6). The other vertical side opposite the calorimeters and pressure taps was covered with rigid surface thermal insulation material. The duel active surface gage probe (fig. 1) was mounted in this insulated side. The insulation was fabricated from 1.54 cm thick material and was bonded to a removable water-cooled metal plate. The probe was inserted through the metal and insulation material with the front surface of the gage flush with the hot surface of the insulation. Four surface thermocouples were laid into uncovered slots fabricated into the surface of the insulation at a position of about 5 cm upstream of the heat flux gage probe position.

EXPERIMENTAL PROCEDURE

The controlling parameters of the arc jet facility are arc current and manifold pressure. There is a prestart condition for the first few seconds of operation. Then the facility is transiently ramped to a steady operating condition. Transient and steady heat fluxes were simultaneously measured with the dual active surface heat flux gage probe and with the six facility reference gages. Simultaneous measurements of insulation material temperatures and facility pressures were also recorded. The heat flux gage probe was first tested with cooling air flowing through the probe at a flow rate of 0.70 gr/sec and at a pressure of 0.8 MPa. Then a second run was performed with no cooling air flowing through the probe. Each of these two runs were performed over a time interval of about 80 sec. Average absorbed heat flux measurements made with the six reference calorimeters were compared with heat flux gage probe measurements. The uncertainty of the absorbed heat flux measurements made with the reference gages mounted in the water-cooled wall is about ±7 percent. Heat flux measured with these reference gages should minimally disrupt the wall temperature because these water-cooled gages are mounted in a water-cooled wall.

RESULTS AND DISCUSSION

Figure 7 presents heat flux data measured with the air-cooled heat flux gage probe and also shows an average of the data measured with the reference gages. Figure 8 shows probe and reference gage heat flux data obtained during a second run when the probe was passively cooled. Also included in figures 7 and 8 are data plots of the arc-current and manifold pressure operating parameters.

In general, the transient and quasi-steady absorbed heat flux histories measured with the actively and passively cooled heat flux gage probe and with the reference calorimeters follow the same time patterns as the arc jet facility operating parameters. These consistent results demonstrate that the heat flux gage probe is fully responsive to changes in environmental conditions.

Correspondence of transient and steady heat fluxes measured with the reference calorimeters and heat flux gage probe was within ±10 percent. Whereas past comparisons of heat flux measurements made with the plug-type gages and with reference gages were within ±20 percent (refs. 1 and 7), the comparisons presented herein were within ±10 percent. This is a significant improvement in plug-type heat flux measurement accuracy.

Figure 9 presents the gas-side surface temperatures of the insulation material surface and of the actively and passively air-cooled heat flux gage probe. After the arc starts, the surface temperatures of the thermal insulation material and heat flux gage increase to a steady-state value. The thermal conductivity and thermal diffusivity of the metal gage is much higher than the surrounding insulation. Thus, the gage is cooler than the insulation because the gage more readily conducts heat from the front surface to the cooling environment at the back surface. As shown in figure 9, the temperatures of these surfaces can differ by a significant 1000K. Even though the gage causes a very large temperature disruption, the correspondence of transient and steady heat fluxes measured with the reference calorimeters and heat flux gages was a very satisfactory ±10 percent.

This good agreement may arise because (1) there is essentially one-dimensional heat transfer along the center line (fig. 4) of the thermoplug, (2) the cylindrical post is integral with the gage body material at the front surface, and (3) the heat sensing element (thermoplug) is located far enough from the edge of the gage body (fig. 4) so that the temperature disruption at the edge of the gage where insulation material and metal meet has a minimal effect on the heat flux measurement obtained within the thermoplug.

CONCLUDING REMARKS

The heat flux measurement results obtained with a miniature dual active surface plug-type heat flux gage probe are presented and compared with commercial reference calorimeters. The heat fluxes were generated in an aerothermodynamic heating arc jet facility located at NASA Ames Research Center. Correspondence of transient and steady heat fluxes was generally within a satisfactory ±10 percent.

The procedure derived herein for measuring surface heat flux is useful because (1) the gage is durable, (2) knowledge of the precise time for application of the method for heat flux measurement is not required, (3) the gage may be cooled, (4) the analysis for heat flux has a statistical basis because least squares curve fit models are used which permit various statistical assumptions for the temperature and property measurement errors, (5) temperature variable properties are permitted, and (6) one-dimensional heat transfer is used in the inverse heat conduction analysis.

The success of this investigation extends the applicability for the dual active surface heat flux gages developed at NASA Lewis Research Center to very thin walls and to thick insulation materials. These gages are small, reliable, accurate and durable. They can be adapted to high temperature, high pressure and high heat flux corrosive and erosive environments generated in combustion or production machinery. For best results, implementation of these miniature plug-type gages should include design analysis and testing at simulated operational conditions.

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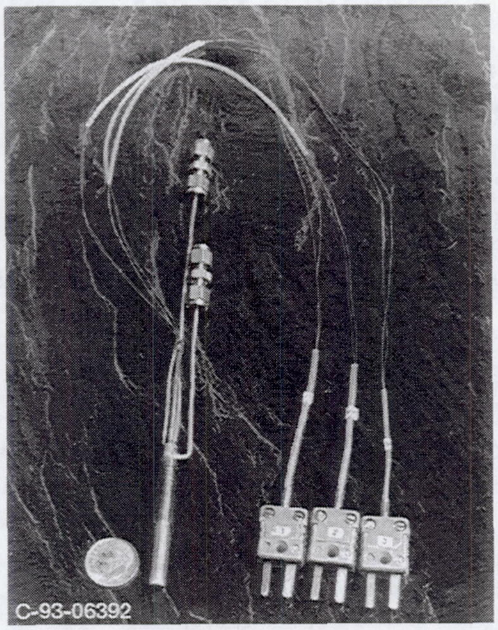

Figure 1.—Dual active surface heat flux gage probe.

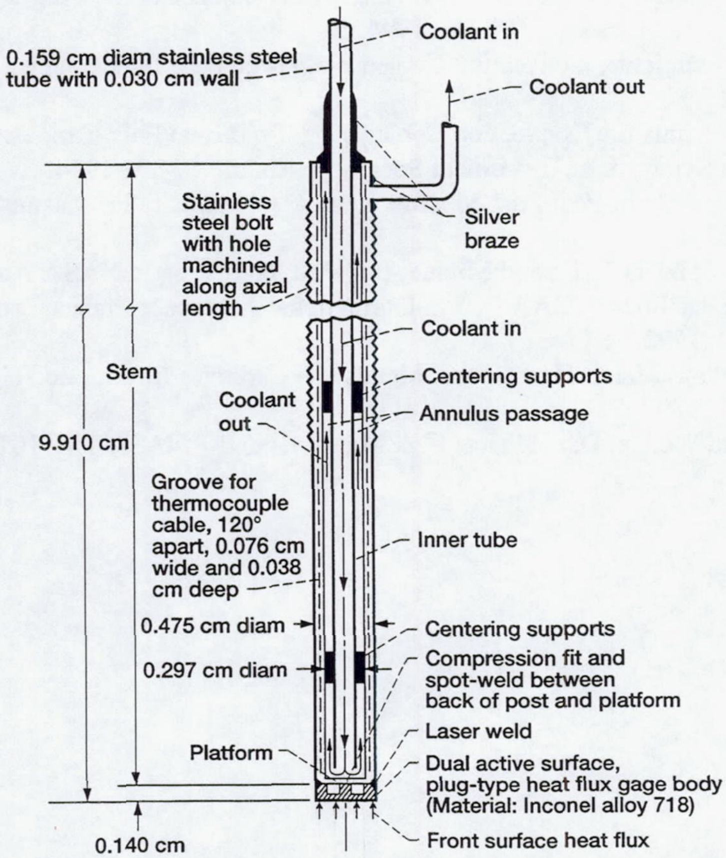

Figure 2.—Dual active heat flux gage probe assembly.

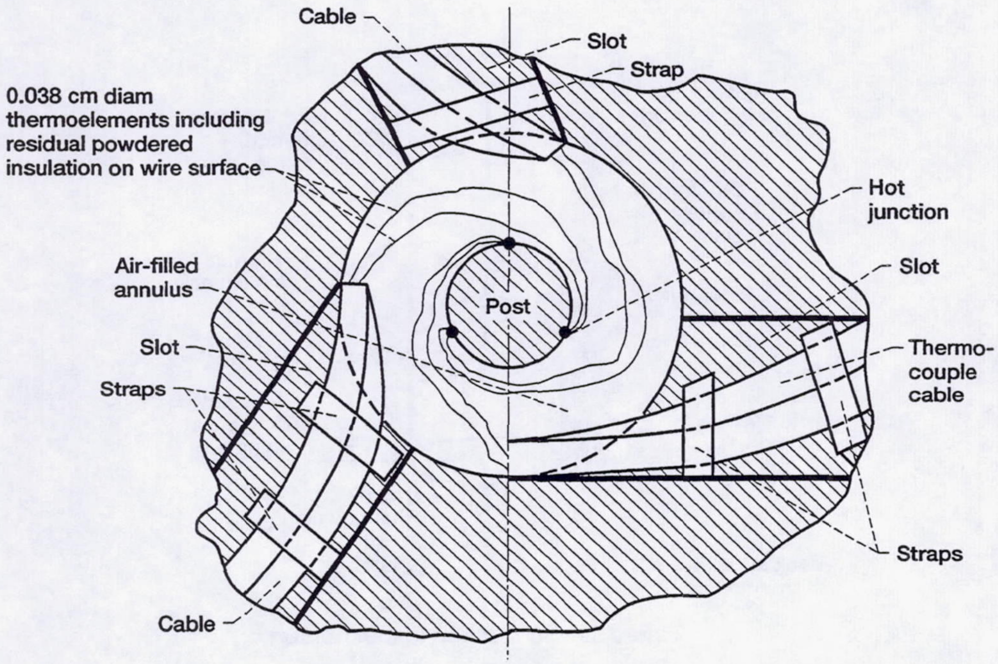

Figure 3.—Top view of heat flux gage body (without stem).

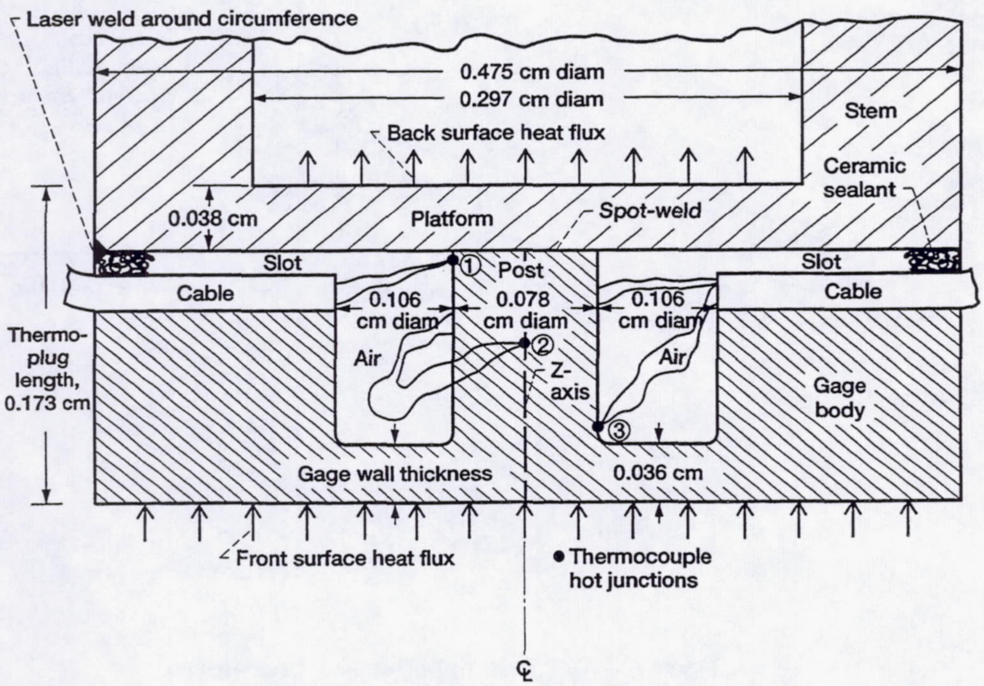

Figure 4.—Side view showing gage body attached to bottom of stem.

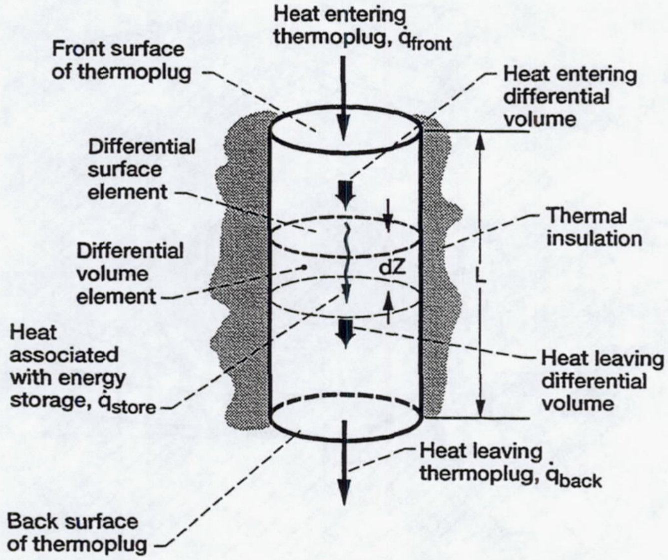

Figure 5.—Conduction in thermoplug.

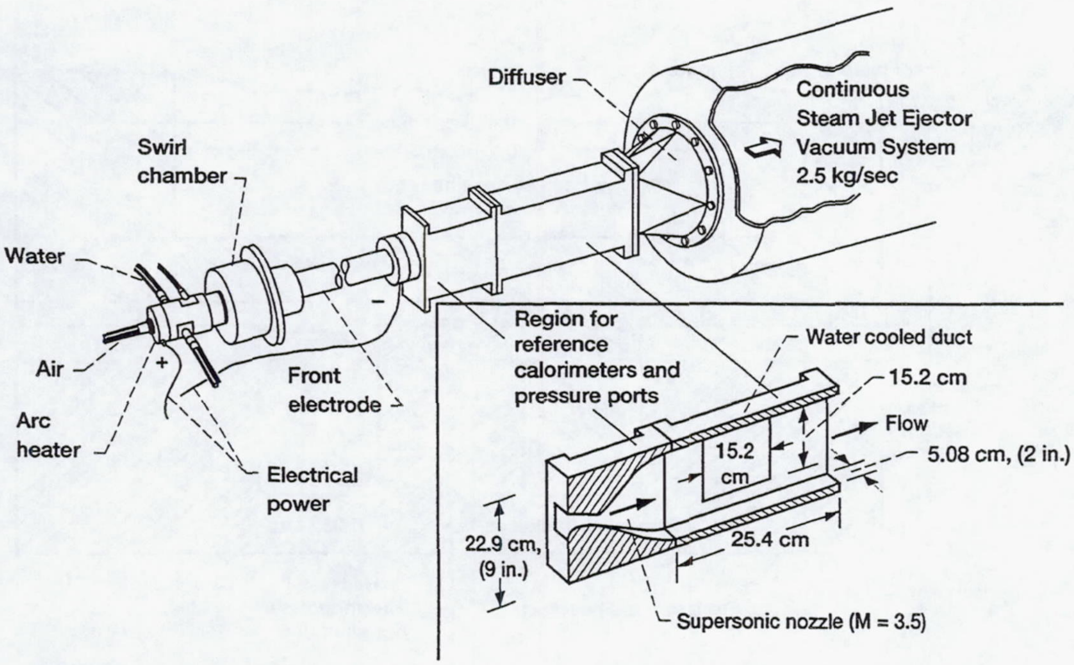

Figure 6.—AMES 2x9 Turbulent Flow Duct Facility.

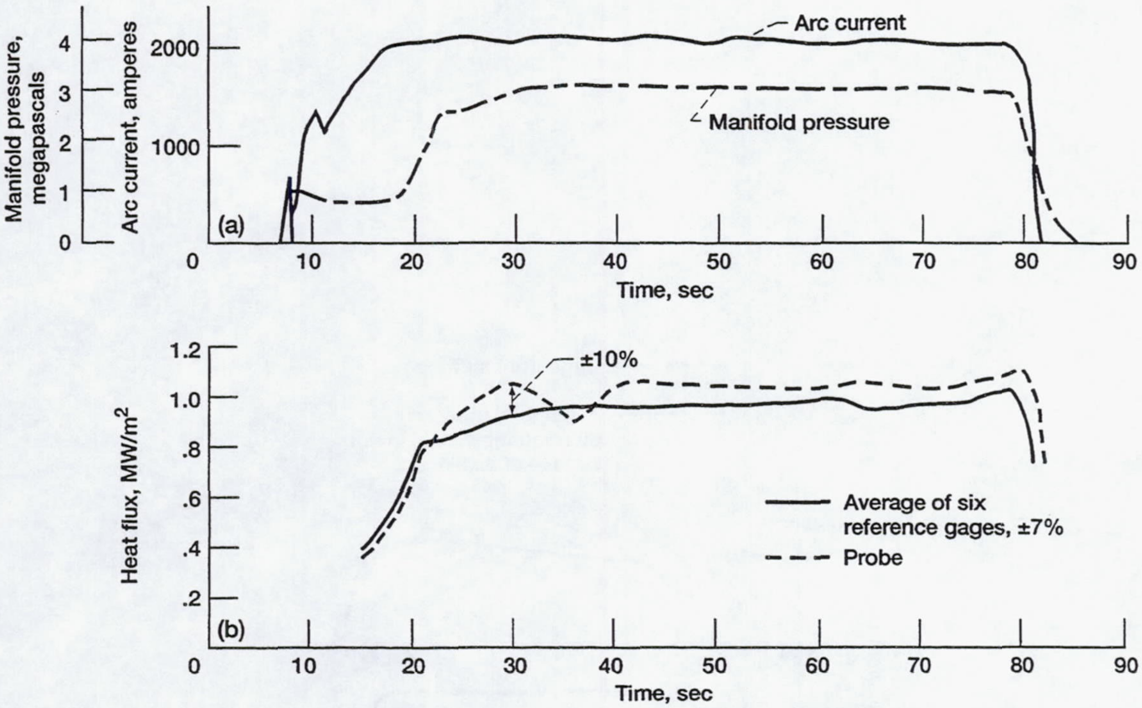

Figure 7.—Heat flux histories measured with reference gages and air-cooled probe. (a) Operating condition of facility. (b) Comparison of heat flux.

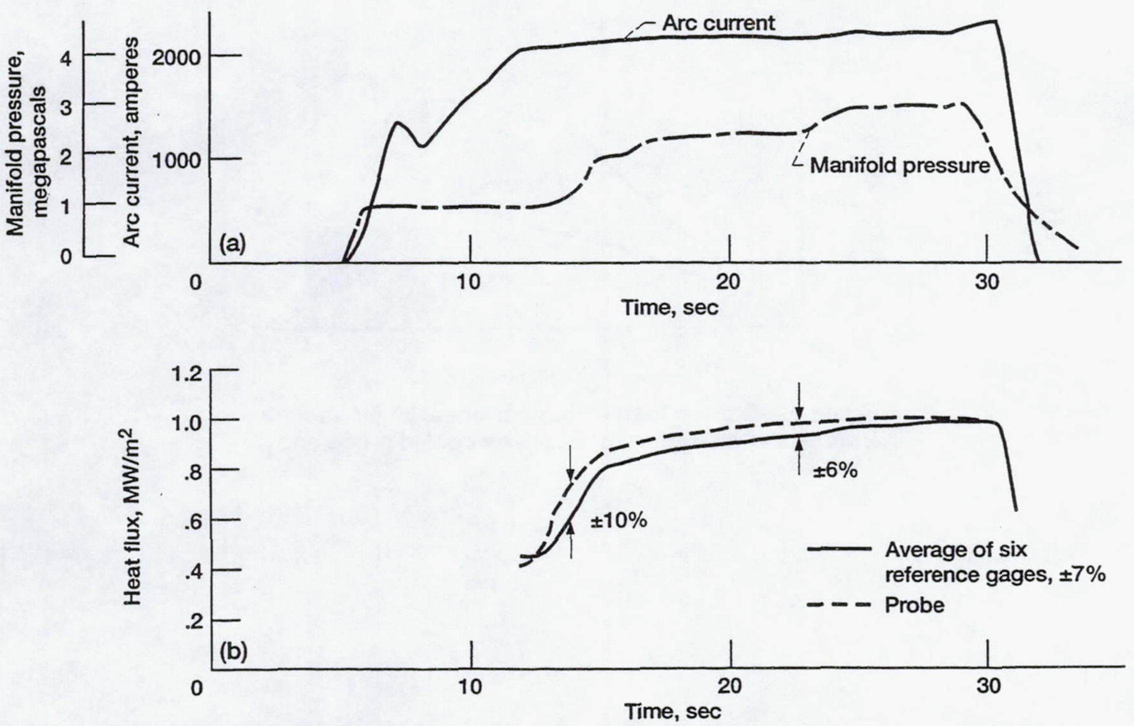

Figure 8.—Heat flux histories measured with reference gages and passively cooled probe. (a) Operating condition of facility. (b) Comparisons of heat flux.

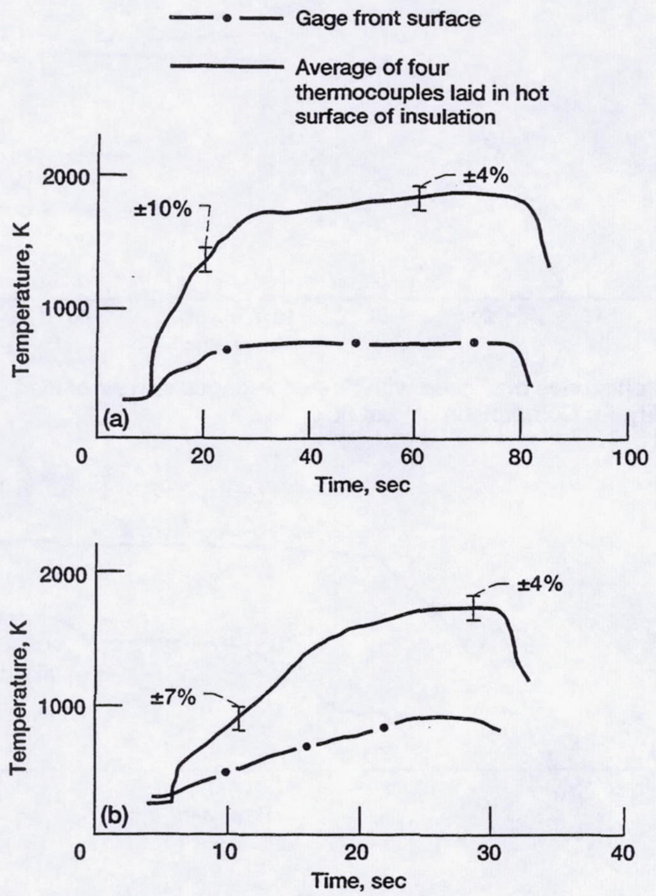

Figure 9.—Surface temperature histories. (a) Air-cooled probe and insulation. (b) Passively cooled probe and insulation.

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13. ABSTRACT ***(Maximum 200 words)***

A unique plug-type heat flux gage probe was tested in the NASA Ames Research Center 2 X 9 turbulent flow duct facility. The probe was fabricated by welding a miniature dual active surface heat flux gage body to the end of a hollow metal cylindrical bolt containing a metal inner tube. Cooling air flows through the inner tube, impinges onto the back of the gage body and then flows out through the annulus formed between the inner tube and the hollow bolt wall. Heat flux was generated in the duct facility with a Huels arc heater. The duct had a rectangular cross section and one wall was fabricated from 2.54 centimeter thick thermal insulation rigid surface material mounted onto an aluminum plate. To measure heat flux, the probe was inserted through the plate and insulating materials with the front of the gage located flush with the hot gas-side insulation surface. Absorbed heat fluxes measured with the probe were compared with absorbed heat fluxes measured with six water-cooled reference calorimeters. These calorimeters were located in a water-cooled metal duct wall which was located across from the probe position. Correspondence of transient and steady heat fluxes measured with the reference calorimeters and heat flux gage probe was generally within a satisfactory $\pm$ 10 percent. This good correspondence was achieved even though the much cooler probe caused a large surface temperature disruption of 1000K between the metal gage and the insulation. However, this temperature disruption did not seriously effect the accuracy of the heat flux measurement. A current application for dual active surface heat flux gages is for transient and steady absorbed heat flux, surface temperature and heat transfer coefficient measurements on the surface of an oxidizer turbine inlet deflector operating in a space shuttle test bed engine.

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