Heat Flux Measurement Using Swept Null Point Calorimetry

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A new technique for measuring the heat flux incident on models tested in high-pressure arc heaters has been developed and demonstrated. The technique consists of sweeping an appropriately designed null point calorimeter across the jet at a rate sufficiently fast not to melt, yet slow enough to permit proper instrument response. This approach has the advantages of 1) measuring the heat flux profile across the entire jet, and 2) saving the instrument for reuse. Numerical heat conduction analyses of null point calorimeters were performed to assess a variety of potential measurement errors and to verify the feasibility of the swept approach. The swept null point technique was utilized to successfully measure the heat flux profile (with $\dot{q}$ peaks as high as 18k Btu/ft^2 sec) across the AFFDL 50 MW RENT arc jet.

Nomenclature

E = thermocouple hole depth, see Fig. 1
L = calorimeter slug length
$OFHC$ = oxygen free high-conductivity copper
P_{t_2} = impact pressure
$\dot{q}$ = heat flux
R = thermocouple hole radius, see Fig. 1
R_N = nose radius of curvature
α = thermal diffusivity
θ = time

I. Introduction

ASSESSMENT of the heat flux level and distribution on models tested in high-pressure arc heaters represents an extremely difficult measurement problem. High pressure (i.e., P_{t_2} order of 100 atm) arc heater facilities are used for testing re-entry vehicle nose tip candidate materials and transpiration cooling systems. Rational interpretation of these test data requires a knowledge of the boundary conditions to which the models are subjected. In particular, it is desirable to measure the rate and distribution of energy transferred to a model, but this is quite difficult because: 1) the test stream is small (order of an inch across) and hence the models are small, 2) the heat fluxes are high (up to 20k Btu/ft^{2}sec), and 3) the heat flux is generally nonuniform in both the radial and axial directions.

Because of their relative simplicity and favorable response time/burn-out time characteristics, transient null point calorimeter models have been the most successful devices for measuring these heat fluxes. A null point calorimeter is a heat flux measuring device configured such that the temperature history measured at some point in depth (the "null point") is the same as the surface temperature history of a semi-infinite solid of the same material subjected to the same incident heat flux. This characteristic enables the heat flux to be calculated from the measured temperature in a simple fashion, i.e., on a 1-*D* basis. Beck and Hurwicz[1] showed that, for suitably high Fourier numbers, this condition is achieved at the end of a hole drilled in a semi-infinite body such that the end of the hole is one hole radius from the heated surface. This "ideal null point" configuration is sketched in Fig. 1. Other null point calorimeter studies have included analytical and experimental investigations by O'Connor and Morgida,[2] and analytical investigation by Howey[3,4] and Howey and DiCristina.[5]

The usual mode of null point calorimeter application has been to hold the calorimeter stationary on the jet centerline. The instrument is usually protected by a Teflon cap (which is ablated off in a fraction of a second) while it is positioned in the jet. Thus, measurements are obtained for only one position in the jet and the instrument is destroyed. Also, previous measurements obtained in this fashion have been less than uniformly successful due to problems associated with nonideal heat conduction effects, unintentional calorimeter movement, and the inability to check the instrument after use.

This article reports a new heat flux measurement technique for high pressure arc heaters which has the advantages of: 1) measuring the radial heat flux distributions across the jet, and 2) saving the instrument for inspection and reuse. The technique consists of sweeping an appropriately designed null point calorimeter across the jet sufficiently fast not to be destroyed, yet slow enough to permit proper instrument response. Swept calorimetry was first suggested in the open literature by Starner,[6] who considered swept thin-skin calorimeters. The present development concentrated primarily on null point calorimeters for two reasons: 1) because of their longer lifetime for very high heat flux conditions, and 2) because they lend themselves more easily to measurement of heat flux distributions to curved surfaces in environments characterized by small dimensions and large heat transfer gradients.

Development and demonstration of swept null point calorimetry consisted of preliminary feasibility studies which utilized numerical heat conduction predictions of calorimeter responses to assumed heat flux profiles, application of the technique to measure heat fluxes in the AFFDL 50 MW RENT arc

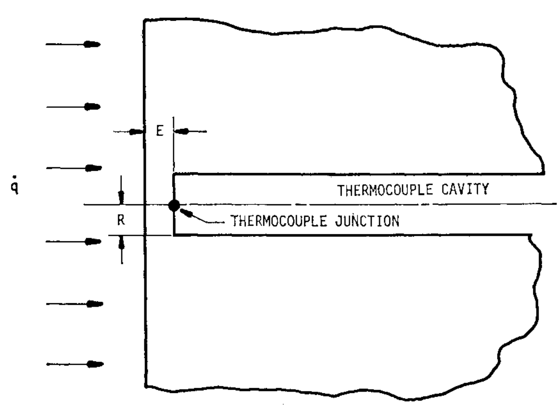

Fig. 1 Ideal null point calorimeter configuration, E = R.

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heater facility, and post-test instrument sectioning, examination and design verification analyses. These activities are documented in detail in Refs. 7–9, and are summarized here. Results of the experimental application of swept null point calorimetry are presented next in Sec. II and feasibility and design verification analyses are described in Sec. III.

II. Experimental Results

The swept null point calorimetry technique was used to perform heat flux measurements as part of the calibration of the AFFDL 50 MW RENT facility. The initial phase of this calibration program included tests designed to assess the viability of the swept null point approach, and some of these results are reported here. Subsequent calibration activities included measurements for a variety of test conditions and model shapes, and these results are documented in Ref. 9.

Facility Description

The Air Force Flight Dynamics Laboratory 50 MW arc is a continuous flow electric arc heated wind tunnel and is the most powerful such facility in operation. In the re-entry nose tip test (RENT) configuration, the facility can produce a steady state stream of air of 1.1 in. diam with a bulk enthalpy of about 2400 Btu/lbm and impact pressures up to 100 atm. Calibration or ablation models are held in five struts of a linear sting system which permits sweeping the models across the jet or holding them in the jet for a predetermined time. The calorimeter evaluation phase utilized a low Mach number contoured nozzle having a 0.9 in. throat and 1.11 in. exit diam. Resulting model stagnation pressures were 80 atm for a 100 atm chamber condition and 95 atm for a 120 atm chamber condition. Models were swept 0.1 in. aft of the nozzle exit plane at 25 to 30 in./sec.

Instrumentation provided by the facility included high speed motion picture coverage, analog data recording (oscillograph) and high sample rate (1000/sec) digital data. At the time of the initial calibration phase, the accurate model position system was not operative but has subsequently been put into service. Hence, the profile data in this article are presented as functions of time only and not position in the jet. Pressure loads on the calorimeter and sting cause the model speed to be slightly different when approaching the jet centerline than when leaving, but for the purpose of examining the technique of swept null point calorimetry a constant sweep speed may be assumed.

Swept heat flux measurements have demonstrated that, for some operating conditions, the RENT jet has a sharp heating spike at its center where the heat flux is about double the jet average. This is believed to be due to a high enthalpy core along the jet centerline which is the result of incomplete heat transfer from the arc column. Recent measurements have shown that this "peaking" is highly dependent on the jet swirl, and that the heat flux profile may be flattened by reducing the swirl (by decreasing the angle of air injection in the heater chamber).

Model Description

Development of the swept null point technique made use of a $\frac{1}{4}$-in. nose radius sphere/cone copper model with a single stagnation point calorimeter slug. A flared model design was used to shorten the model such that the altered shock pattern could not influence stagnation heat rates. Figure 2 shows this model and the calorimeter slug geometry. A flange on the rear of the null point slug was used for retention. The flange was clamped to its seat by a hollow push tube and clamp nut. Each slug was carefully fitted both in diameter and length to its mating hole, and cleanup machining was performed on the assembled instrument, taking care not to remove any material from the junction area (centerline) of the slug. Three mil chromel/alumel thermocouple wires were spot welded to larger lead wires and the joint potted for strain relief. An outer braid electrical shield was used on the thermocouple leads exterior to the model and was terminated to the model base.

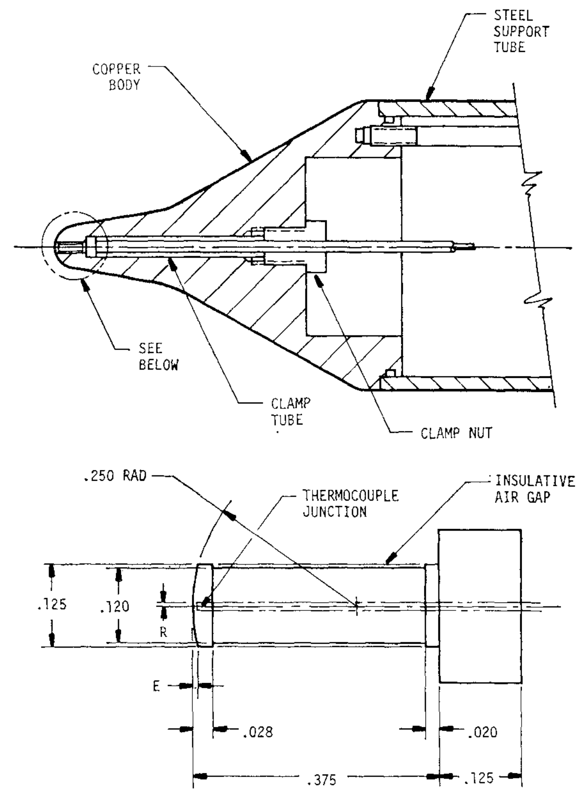

Fig. 2 Calorimeter model and slug detail.

As part of the facility calibration program, models designed to measure heating distributions over various shapes were also successfully tested in the swept mode. These had spherical, blunt and conic shapes, and as many as three null point calorimeter slugs per model. Design details and test results for these models are discussed in Ref. 9.

Swept Heat Flux Measurement

Calorimeter sweeps across the arc jet were performed for several runs at nominal model stagnation pressures of 80 and 100 atm. Figure 3 shows the results obtained using a calorimeter swept at 30 in./sec for the $P_{t2} = 100$ atm condition. Figure 3 shows both the measured temperature history and the calculated heat flux. This example was selected since it represents the most severe test of the transient characteristics of the null point due to the high value and short interval of the heating spike. The shape of the heat flux history is typical of most runs, but the peak centerline heating value is higher than the centerline averages obtained over several runs, which were about 15k Btu/ft^2 sec and 16k Btu/ft^2 sec for the nominal 80 and 100 atm impact pressure conditions, respectively.

Stationary Heat Flux Measurement

Previous testing using null point calorimeters at high pressure arc jet facilities utilized the stationary mode. The calorimeter is protected from premature heating by a Teflon cap as it is rapidly swept into the stream and locked on centerline. Ideally, the model is settled at the centerline when the cap is impulsively removed by an ablative-pressure load failure. Thereafter, the centerline heating value is measured, and the calorimeter destroyed. Several calorimeters were tested in this mode to establish a base line of evaluation of the swept mode.

Figure 4 shows the temperature and reduced heat flux history of a stationary measurement at 82 atm model

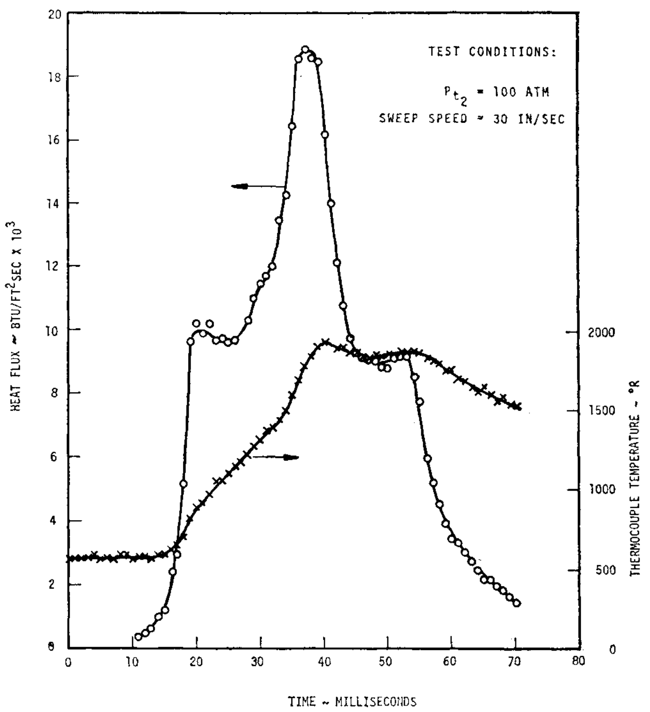

Fig. 3 Typical swept null point calorimeter measurement; thermocouple temperature history and corresponding heat flux profile.

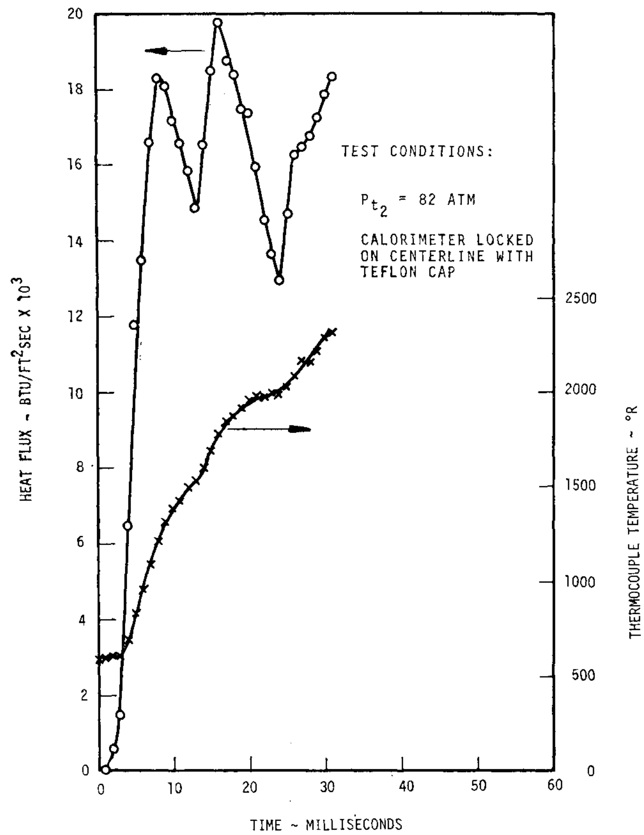

Fig. 4 Typical stationary null point calorimeter measurement; thermocouple temperature and corresponding heat flux.

stagnation pressure. A probable explanation of the waviness of the heat flux is that the model was still mechanically oscillating because of the sudden stop and hence moving in and out of the central heating spike. Examination of motion picture data during this time shows a frequency and amplitude of model oscillation which could account for the heating oscillation. The film data showed a clean removal of the Teflon cap. Considering this uncertainty, and the expected 10% higher heating associated with a $P_{t_2} = 100$ atm condition relative to an 82 atm condition, it is observed that the "stationary" heat flux measurement shown in Fig. 4 is essentially consistent with the swept profile shown in Fig. 3.

III. Measurement Accuracy

In order to assess the accuracy of the heat flux measurements, numerical heat conduction analyses were performed to quantify errors resulting from "nonideal" null point behavior and to verify that the instrument response was sufficient to "follow" the nonuniform heat flux profile. Also, calorimeters were nondestructively tested prior to use to verify their thermal response and selected calorimeters were sectioned after use (in the swept mode) to enable microscopic inspection of the critical thermocouple junction.

Analysis of Measurement Errors—Stationary Mode

The performance of actual null point type calorimeters departs somewhat from that of "ideal" null point calorimeters as previously defined because of constraints imposed by design and manufacturing considerations. Design constraints include finite slug length and diameter, and a frequent requirement for surface curvature. Manufacturing imperfections include 1) variations in thermocouple hole depth, 2) the existence of braze alloy in the hole, and 3) increased thermal impedance between the heated surface and thermocouple junction resulting from imperfect thermocouple bonding to the bottom of the hole and from alloying of the calorimeter material by the braze material. Previous studies of the heat flux measurement errors due to nonideal null point behavior include Refs. 4 and 5. These investigations report substantial errors for some cases, but present no generalized results or design guide lines.

In order to assess, for the conditions of interest here, the magnitude of errors due to nonideal null point behavior, numerical heat conduction analyses were performed utilizing the computer code described in Ref. 10. This code employs an alternating direction implicit-explicit scheme to solve the transient heat conduction equation for axisymmetric bodies with temperature dependent material properties and subjected to arbitrary boundary conditions. Analyses were performed to characterize the response of a typical "real" null point calorimeter, to individually assess a variety of potential errors, and to verify the swept mode response of a null point calorimeter.

Computer modeling of typical calorimeter

The heat flux measurement errors associated with "ideal" null point data reduction for a typical real calorimeter were assessed in the following manner: 1) Specify an incident heat flux distribution and perform a transient 2-*D* heat conduction analysis of the actual calorimeter, taking care to account for all nonideal heat conduction effects. 2) Input the predicted thermocouple temperature history as the surface temperature of a semi-infinite solid (i.e., ideal null point data reduction). 3) Compare the heat flux history calculated in 2 to that specified in 1—the difference is the measurement error.

A typical null point calorimeter configuration, similar to that shown in Fig. 2, was analyzed in this fashion. Details of these analyses are presented in Ref. 8, and the results are summarized here. Aspects such as the 2-*D* conduction, the curved surface, the insulative air gap, etc., were modeled. Laminar, time constant heating distributions with stagnation point rates of 5, 10, and 15k Btu/ft² sec were considered. These computations indicated that, at least for this configuration and for time constant (i.e., stationary mode) heat fluxes, net measurement errors due to nonideal heat conduction errors are quite small (less than 2% after a brief response time to be discussed subsequently).

Assessment of individual errors

In order to establish guide lines for null point calorimeter design and data reduction, analyses were performed to individually assess the measurement errors associated with a variety of non-ideal aspects of actual calorimeters. These analyses were performed by numerically modeling the instrument thermal response in a fashion similar to that described above.

1) Finite slug length. The ideal null point concept is based on a semi-infinite solid. Reference 5 shows that a null point calorimeter is effectively semi-infinite so long as $\alpha\theta/L^2 < 0.3$ (e.g., for $\dot{q} = 10$k Btu/ft^2 sec, an OFHC copper calorimeter should be at least 0.2 in. long). Calculations performed verified that much shorter slugs may be used (e.g., $L = 0.1$ in. for the above conditions) if thermocouple data is reduced as the surface temperature of a 1-*D* slab of thickness equal to the calorimeter length, rather than as the surface temperature of a semi-infinite solid as per the usual null point convention. Such short calorimeters are more adversely affected by heat leaks, so care should be taken to assure a high thermal resistance between the calorimeter slug and the surrounding body.

2) Hole-to-slug radius ratio. The measurement error due to the finite slug diameter depends on the hole diameter, heat flux, and time. For the conditions of interest here, calculations demonstrated that the measurement error will be less than 3%, as long as the hole-to-slug diameter ratio is less than 0.2.

3) Calorimeter face curvature. The ideal null point calorimeter has a flat face. However, most calorimeters are used to measure the heat flux to curved bodies (e.g., a spherical nose). The curved face causes two effects: the incident heat flux is nonuniform and the heat conduction geometry is perturbed. For laminar stagnation point flow, these effects are approximately compensating. Analyses indicated that this error increases with $\alpha\theta/R_N{}^2$ but that it is negligible for heat fluxes and geometries of interest here. Calorimeter models with curved faces should be designed with $R_{slug}/R_N <$ 0.3 and a large thermal resistance between the slug and model body.

4) $E \neq R$. The ideal null point configuration requires that the hole depth equal the hole radius. This represents a difficult machining problem for the very small holes of interest here ($R \sim 0.01$ in.). Also, the thermocouple junction braze, and alloying of the slug material with the braze, can substantially alter the effective E. For a given E, errors due to $R \gg E$ become very large but errors due to $R < E$ are bounded by the $R = 0$ situation. Two specific cases were analyzed for a heat flux history similar to that shown in Fig. 3. $E<R$: if data from a calorimeter with $E = 0.005$ in. and $R = 0.012$ in. is reduced in the ideal null point fashion, the calculated peak heat flux will be 20% higher than the actual heat flux. $E > R$: if data from a calorimeter with $E = 0.012$ in. and $R = 0$ is reduced in the ideal null point fashion, the calculated peak heat flux will be 20% low.

5) Thermocouple wire conduction. Errors due to conduction along the thermocouple wires were estimated by considering the wires to be attached to a slab of thickness E which is exposed to a constant heat flux (Ref. 11 presents a closed-formed solution for this situation). This analysis, which is quite approximate but conservative for null point calorimeters, indicated an error of about 1% for the conditions of interest here.

6) Thermal impedance due to alloying. The usual practice in null point calorimeter construction is to employ a high temperature braze or solder to affix the thermocouple junction to the bottom of the hole. During the brazing operation, the assembly is held at a high temperature for some time so the braze will tend to form an alloy with the slug material (usually OFHC copper). This alloy will have a thermal conductivity far less than that of copper and thus it will affect the heat flux measurement. Numerical analyses considered an 80% Au/20% Cu alloy with an α about $\frac{1}{6}$ that of OFHC copper. These analyses indicated the effect on the heat flux to be negligible if the alloy is confined to a thin layer ($< E/5$) at the bottom of the thermocouple hole. Added thermal impedance (e.g., due to alloying) can have a significant effect on the response of the calorimeter in the swept mode, and this will be considered subsequently.

7) Heat leaks from the calorimeter slug. Null point calorimeter slugs are usually installed in the supporting bodies in a fashion such as to provide a smooth sealed surface while, to the extent possible, insulating the slug from the body (e.g., Fig. 2). For long slugs ($\alpha\theta/L^2 < 0.3$), this insulation is not particularly critical except in the case of severe face curvature (see item 3). However, short slugs ($\alpha\theta/L^2 > 0.3$ —see item 1) will heat up faster than the surrounding body and so heat leaks may occur which can affect the heat flux measurement. The magnitude of this effect was estimated by analyzing a short slug supported at its flanges. The contact resistance at the flanges was estimated to be 0.4 ft^2 sec °R/Btu and the resistance across the air gap can be shown to be effectively infinite. For these conditions, the measurement error due to heat leaks was less than about 2% if $\alpha\theta/L^2 < 0.6$.

8) Temperature data scatter. The possibility of specifying the unsmoothed thermocouple data directly to the 1-*D* conduction solution to obtain the heat flux was investigated. It was found that, for typical temperature data scatter of ± 5°R, the heat flux calculated in this fashion is not as smooth but has the same average level as the heat flux calculated from hand smoothed thermocouple data.

Swept mode analysis

In the swept mode, the calorimeter transient response must be sufficient to permit accurate measurement of the profile for sweep rates fast enough to avoid melting and for thermocouple hole depths (E) within the range of manufacturing practicality. Beck and Hurwicz[1] showed that the null point location is within 10% of its steady state location ($E/R = 1.0$) for $\alpha\theta/E^2 \geq 30$, and this is often incorrectly taken as the "response time" of null point calorimeters (e.g., Refs. 2 and 3). The previously described numerical analyses demonstrated that, for null point calorimeters subjected to time constant heat fluxes, the computed heat flux will be within 5% of the steady state value for $\alpha\theta/L^2 \geq 3$. However, null point calorimeters do not have a simple exponential response and it is difficult to apply this criteria to assess the response to a time varying heat flux. To verify the accuracy of the swept null point calorimeter measurements, complete transient 2-*D* (axisymmetric) numerical heat conduction analyses were performed.

Prior to the experimental application of this technique, numerical analyses were carried out using an assumed heat flux profile (taken from Ref. 12). These analyses indicated the swept approach to be feasible.

After the experimental results were obtained, additional analyses (using the measured heat flux profiles) were carried out to verify the accuracy of the measurements. These analyses followed the procedure described previously and some typical results are shown in Fig. 5. This figure compares the measured heat flux profile which was specified to the complete 2-*D* analysis to the heat flux profile resulting from simple "ideal null point" 1-*D* data reduction of the thermocouple temperature history predicted by the 2-*D* analysis. The conditions analyzed here are those of the high pressure condition stagnation point measurement shown in Fig. 3 ($E = R = 0.011$ in. and sweep rate ≈ 30 in./sec). Figure 5 clearly shows no significant measurement errors or time lags for this case.

The response of a null point calorimeter in the swept mode is critically dependent on good thermal contact between the thermocouple junction and the hole bottom. A real calorimeter will have some additional thermal impedence due to too much or two little solder, alloying, etc. The design verification analyses described above assumed a massless thermocouple junction to be in perfect thermal contact with a pure OFHC copper slug. Numerical analyses were carried out in order to assess the effect of additional thermal impedance on null point calorimeter response in the swept mode. The approach taken was to add fictitious resistance and capacitance to the 2-*D* numerical model. The magnitude of this impedance was estimated by matching, with the numerical model, the initial response of a stationary mode heat flux measurement (as shown in Fig. 4). The added resistance x capacitance was about 0.0007 sec. This numerical model was then used to re-predict the transient 2-*D* response of a "real" calorimeter to the heat flux profile shown in Fig. 3. The predicted thermocouple response was reduced as ideal null point data. The heat flux profile calculated in this fashion is also compared to that specified to the 2-*D* solution in Fig. 5. This figure shows that the additional impedance causes the measurement to "lag" the actual heat by about 0.002 sec and decreases the peak measurement by about 4%.

Quality assurance

Quality assurance requirements include 1) a means to verify that design and manufacturing constraints have been met, and 2) a need for post-test examination of certain calorimeters which may yield apparently anomolous results. The first requirement must be satisfied with nondestructive techniques. The ideal NDT technique would involve calorimeter exposure to a known heat flux in the range of intended application. A technique utilizing a high intensity radiation source for this purpose is currently under development.

The present investigation employed compromised NDT techniques consisting of 1) x-ray to verify thermocouple junction depth and 2) exposure to a high energy pulsed laser accompanied by accurate measurement of a characteristic temperature rise time§ in order to detect high thermal impedance representative of a poor thermocouple bond. This latter technique was suggested and implemented by Denman.[13] Pulsed laser exposure should also be employed after installation of the null point slug into the calorimeter body to insure the junction has not been disturbed during installation.

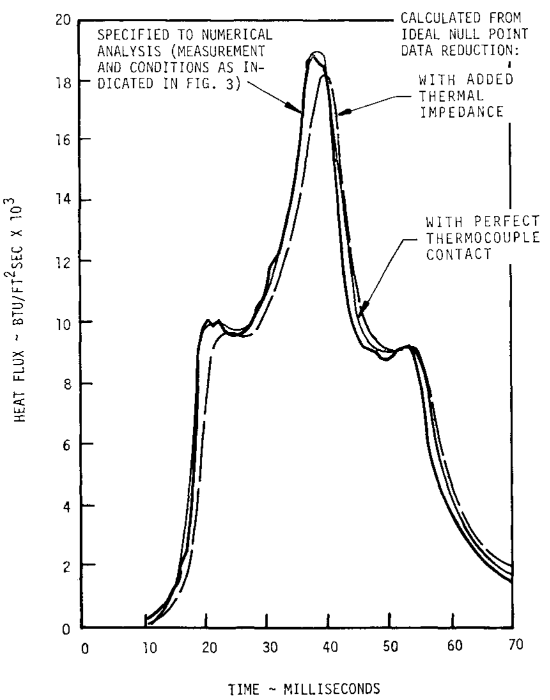

Fig. 5. Results of swept mode calorimeter response analysis; thermocouple response predicted by transient 2-*D* numerical analysis was reduced as "ideal" null point data to obtain heat fluxes.

§Typically, the time required for half the maximum temperature to be reached.

The most effective technique for post-test evaluation of suspect null point slugs is to remove them from the calorimeter body and section them along the thermocouple probe axis. Photomicrographs of numerous sectioned null point calorimeters are shown in Refs. 8 and 9. It is observed that calorimeters which responded well generally have a well machined flat bottomed hole and good thermal contact between the thermocouple junction and the copper body with no excess of braze alloy. Conversely, the reason for poor response from a given calorimeter is usually evident from an examination of the sectioned slug.

IV. Conclusions

1) Null point calorimeters operated in the swept mode represent a new better way to measure heat fluxes in high pressure arc jet environments. 2) Multiple calorimeter exposures in the AFFDL 50 MW arc jet facility have demonstrated that a swept null point calorimeter may be repeatedly used to measure heat flux levels up to 20k Btu/ft^2-sec. Extensive numerical error analyses considering design constraints and manufacturing variations indicate that the accuracy of these measurements is within $\pm 10\%$. 3) Instrument response time with current manufacturing and NDT techniques is sufficiently fast to enable accurate measurement of sharply peaked heat flux profiles characteristics of high pressure arcjets at certain operating conditions.

References

[1] Beck, J. V. and Hurwicz, H., "Effect of Thermocouple Cavity on Heat Sink Temperature," *Journal of Heat Transfer*, Vol. 82, No. 1, Feb. 1960, pp. 27–36.

[2] O'Connor, T. J. and Morgida, J. F., "Null Point Transient Calorimeters, Theoretical Concepts and Experimental Results," Preprint 16.5–2–66, Oct. 1966, Instrument Society of America.

[3] Howey, D. C., "A Two-Dimensional Study of Miniaturized Calorimetric Techniques for Extreme Stagnation Heating Rates (3000-10000 Btu/ft^2 sec)," Preprint 16.5–3–66, Oct. 1966, Instrument Society of America.

[4] Howey, D. C., "Response Time and Burnout Lifetime Optimization for Miniaturized Null Point Conduction Calorimeters," Preprint P6–4–PHYMMID–67, Sept. 1967, Instrument Society of America.

[5] Howey, D. C. and DiCristina, V., "Advanced Calorimetric Techniques for Arc Plasma Heat Transfer Diagnostics in the Heat Flux Range up to 20 KW/cm^2," AIAA Paper 68–404, San Francisco, Calif., 1968.

[6] Starner, K. E., "Use of Thin-Skinned Calorimeters for High Heat Flux Arc Jet Measurements," Preprint P11–5–PHYMMID–67, Sept. 1967, Instrument Society of America.

[7] Rindal, R. A., et al., "High Pressure Ablation Characterization of Graphite for Nose Tip Applications," *Graphitic Materials for Advanced Re-entry Vehicles, Part I*, edited by D. M. Forney Jr., AMFL–TR–70–133, Pt. 1, Aug. 1970.

[8] Kennedy, W. S., et al., "AFFDL 50 MW RENT Facility Calibration—First Monthly Progress Report" for Contract F33615–70 –C–1105, Feb. 1970, Aerotherm Corp., Mountain View, Calif.

[9] Green, K. A., et al., "AFFDL 50 MW RENT Facility Calibration—Second Quarterly Progress Report," for Contract F33615–70 –C–1105, June 1970, Aerotherm Corp., Mountain View, Calif.

[10] Moyer, C. B., "Axi-Symmetric Transient Heating and Material Ablation Program (ASTHMA) Description and User's Manual," Rept. 68–27, Jan. 1968, with Addendums 1–8, Aerotherm Corp., Mountain View, Calif.

[11] Burnett, D. R., "Transient Temperature Measurement Errors in Heated Slabs for Thermocouples Located at the insulated Surface," *Journal of Heat Transfer*, Vol. 83, No. 4, Nov. 1961, pp. 505–506.

[12] Smith, R. T. and Folck, J. L., "Operating Characteristics of a Multi-Megawatt Arc Heater Used with the Air Force Flight Dynamics Laboratory 50-Megawatt Facility," AFFDL–TR–69–6, April 1969, Air Force Flight Dynamics Lab., Wright-Patterson Air Force Base, Ohio.

[13] Denman, G. L., private communication, Jan. 1970, Air Force Materials Lab. Wright-Patterson Air Force Base, Ohio,