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▶ This paper describes a method of determining the transient heat flux to the plane or cylindrical surface of an isotropic material. The method is applicable when the material is initially at a known temperature without heat transfer, and then is suddenly subjected to heat transfer at one surface. Temperature measurements made on or near the heat transfer surface are used as boundary conditions for numerical solution of the transient heat conduction equation, enabling the temperature distribution within the material to be determined. The properties of the material may vary with temperature. Heat flux is computed as the product of the temperature gradient and the thermal conductivity at the surface. Experimental results from rocket motor testing indicate that the method can be used to determine local heat flux in combustion chambers and nozzles where the heat flux is known to vary in both circumferential and axial directions.

Abst

CALCULATION OF HEAT TRANSFER RATE FROM TRANSIENT TEMPERATURE MEASUREMENTS

When a mass of material initially at a uniform temperature is suddenly subjected to heat transfer at one surface, the surface heats up rapidly, and heat is conducted back into the bulk of the material. Initially, only the material near the surface is heated; as time goes on, a thicker and thicker layer of material is affected. As long as heat is being transferred into the body through the surface, the temperature of the body will be highest at its surface, and will decrease rapidly to approach the undisturbed temperature at some distance back of the surface, as shown in Figure 1. The temperature rise at the surface and the temperature distribution within the body will depend on the thermal conductivity and the heat capacity of the body as well as on the incident heat flux. Conversely, the temperature rise at or near the surface, if measured, can be used to determine both the temperature distribution within the body and the incident heat flux. This is the basis of an analysis which leads to a practical method of calculating the heat flux from measurements of the temperature changes on or near the heat transfer surface.

Consider an infinite hollow cylinder of isotropic material having known but temperature-varying thermal

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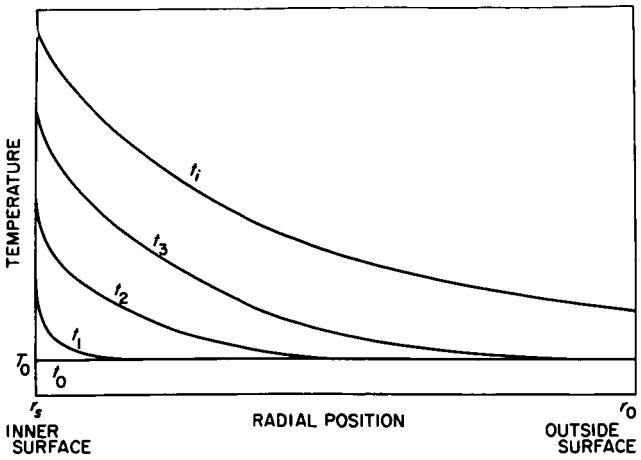

Figure 1. Temperature distribution within wall as a function of time.

properties. The inside surface of this cylinder is subjected to a uniform heat flux. The equation for radial one-dimensional heat flow through the wall of a cylinder is[1]

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(k \frac{\partial T}{\partial r}\right) + \frac{k}{r}\frac{\partial T}{\partial r} \tag{1}$$

Given certain boundary conditions, which can be obtained from experimental measurements, this equation can be solved by numerical methods to obtain the complete temperature distribution within the wall of the cylinder at any time. If the interior temperature distribution is known, the temperature gradient at the surface can be found. Then the heat flux to the surface is given by the following equation:

$$q = -\left(k \frac{\partial T}{\partial r}\right)_{\text{surface}} \tag{2}$$

The boundary conditions required for the solution developed herein are (1) the time variation of temperature at two separate points along a given radial path, and (2) an initial temperature distribution between these two points. One of the measured temperatures should be at or close to the heat transfer surface; if it is not at the surface, the temperature and temperature gradient at the surface must be obtained by extrapolating a curve fitted to the temperature distribution between the two measured temperature points. The second position at which the boundary condition temperature is measured can conveniently be the outside surface of the cylinder. It should be noted that the temperature of the outer point may or may not vary with time, depending on the wall thickness, the heat flux, and the duration of the test. Where a relatively thick wall is subjected to heat flux for a short time the heat will penetrate only a short distance, and the solution will correspond to the case of a semi-infinite solid.

The numerical solution of equation (1) is obtained in the following manner: Consider that the region between the two measured temperature points is divided into many increments of length Δr, and that boundary condition temperature measurements are obtained at time intervals Δt. Then a time–position grid can be constructed on which measured and calculated temperatures can be entered, as shown in Figure 2.

The first calculated interior temperature point, T_{t_2,r_1} is obtained by writing the difference forms of the differential equations as follows:

$$T_{t_2, r_1} = T_{t_1, r_1} + \left(\frac{\partial T}{\partial t}\right)_{t_1, r_1} \Delta t =$$

$$= T_{t_1, r_1} + \frac{1}{(\rho c_p)_{t_1, r_1}}\left[\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right) + \frac{k}{r}\frac{\partial T}{\partial r}\right]_{t_1, r_1} \Delta t \tag{3}$$

$$\left(\frac{\partial T}{\partial r}\right)_{t_1, r_1} = (T_{r_2} - T_{r_T})_{t_1}/2\Delta r \tag{4}$$

$$\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)_{t_1, r_1} =$$

$$= \frac{[(k_{r_2} + k_{r_1})(T_{r_2} - T_{r_1}) - (k_{r_1} + k_{r_T})(T_{r_1} - T_{r_T})]_{t_1}}{2\Delta r^2} \tag{5}$$

If the relationship of equation (1) is used, equations (4) and (5) can be substituted in equation (3) to obtain the equation used for the digital calculation

$$T_{t_2, r_1} = T_{t_1, r_1} + \frac{\Delta t}{2\Delta r^2 (\rho c_p)_{t_1, r_1}}[(k_{r_2} + k_{r_1})(T_{r_2} - T_{r_1}) - (k_{r_1} + k_{r_T})(T_{r_1} - T_{r_T}) + \frac{\Delta r k_{r_1}}{r_1}(T_{r_2} - T_{r_T})]_{t_1} \tag{6}$$

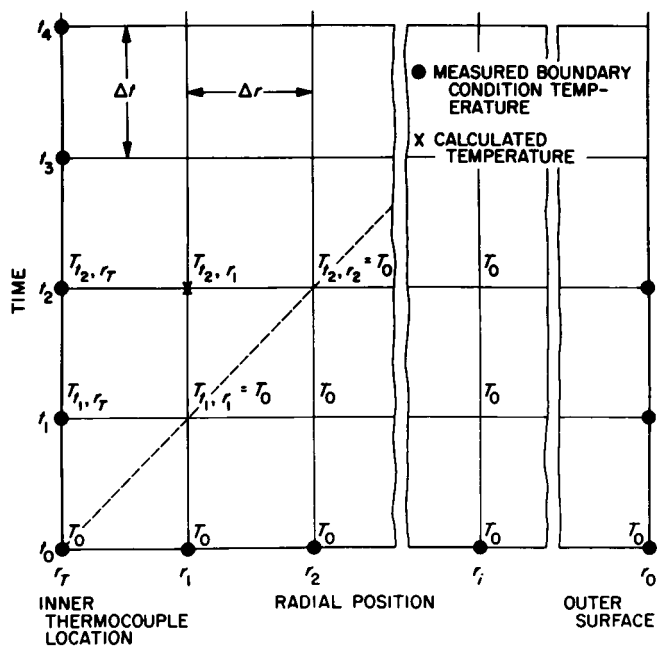

Figure. 2. Position–time mesh for calculation of temperature distribution.

Subsequent points are calculated in the same manner.

In selecting the mesh increments, Δr and Δt, it is necessary that a stability criterion be recognized: thus,[2]

$$\frac{\Delta t}{\Delta r^2} \leqslant \frac{1}{2} \frac{1}{(k/\rho c_p)_{\max}} \tag{7}$$

If this criterion is satisfied, numerical and round-off errors tend to damp out with increasing time.

When the temperature distribution between the two boundary condition thermocouples within the cylindrical wall has been developed as a function of radial position and time, the next step is to determine the temperature and the temperature gradient at the heat transfer surface at various times. If the inner boundary temperature measurement has been made behind the heat transfer surface, it will be necessary to fit a curve to the radial temperature distribution in the region nearest the surface. This curve can then be extrapolated to give the temperature at the surface and differentiated to obtain the radial temperature gradient at the surface. When the inner boundary temperature measurement is made at the heat transfer surface, the same curve fitting and differentiating process can be used to determine the radial temperature gradient at the surface, but the extrapolation step is omitted.

A fifth-order polynomial function fitted to six equidistant points in the temperature distribution has been used successfully in extrapolating temperatures to the wall, where required, and in determining the temperature gradient at the wall.[3] When extrapolation is involved, the spread of the points to which the curve is fitted should be several times the extrapolation distance in order to define the curve adequately. Usually the first six temperature mesh points are used, but if necessary every second or third point can be used to extend the base of the curve. Other forms for the curve-fitting function have been investigated, but none seems superior to the fifth-order polynomial.

When the inner temperature is measured at the heat transfer surface and no temperature extrapolation is required, a simple digital difference approach similar to that used in calculating the temperature distribution can be used to approximate the temperature gradient at the wall. Thus, at any time

$$\begin{aligned}\left(\frac{dT}{dr}\right)_{\text{wall}} &= \left(\frac{dT}{dr}\right)_{r_1} + \left(\frac{d^2T}{dr^2}\right)_{r_1} \Delta r \\ &= -[(T_{r_T} - T_{r_2})/2\Delta r \\ &\qquad + \{(T_{r_T} - T_{r_1}) - (T_{r_1} - T_{r_2})\}/\Delta r] \\ &= -\frac{1}{\Delta r}[\tfrac{3}{2}T_{r_T} + \tfrac{1}{2}T_{r_2} - 2T_{r_1}]\end{aligned} \tag{8}$$

This evaluation uses only the measured wall temperature and the calculated temperature at the first two interior radial stations.

The entire process of calculating the interior temperature distribution from the measured boundary temperatures, fitting the curve to the temperature points, determining the temperature gradient at the wall, and calculating the heat flux can be programmed for a digital computer. This has been done at the Jet Propulsion Laboratory, and many solutions have been obtained.

EVALUATION OF METHOD

The numerical solution method described in the previous section has been tested by using as input data surface temperatures derived from the analytical solution of the problem of heat transfer to a flat plate with prescribed heat flux at one surface.[4] It was found that the interior temperature distribution could be closely approximated by the digital calculation procedure. In one typical calculation the temperatures just behind the measured surface temperature were a few degrees high at the start of the calculation and gradually approached the true temperatures as time increased. The accuracy of the calculation of the internal mesh temperatures could, in theory, be improved to any desired extent by using smaller time and radius calculation increments, although this might not be possible in practice, where data acquisition rates are limited and the shape or scatter of the input data can make interpolation impracticable.

The determination of the radial temperature gradient near the surface depends both upon the accuracy with which the digital calculation procedure can give the interior mesh-point temperatures and upon the form of the curve which is fitted to the calculated points to obtain the slope at the surface. Both the fifth-order polynomial and the simpler digital difference equation, equivalent to a second-order polynomial function, gave satisfactory values of the surface temperature gradient at about the same time as the calculated internal temperatures converged on the true internal temperatures. The combined limitation of the calculation and curve-fitting procedures seems to be such that up to 50 or even 200 calculation time intervals may be required before convergence on the true heat flux is achieved when, as in the analytical problem, there is an instantaneous application of heat flux to the surface of the body.

On the other hand, when the steady heat flux is preceded by a transition period of gradually increasing heat flux and wall temperature, convergence to within a few percent of the true heat flux may be attained in only 20, or even fewer, calculation time intervals after the steady heat flux conditions are established.

The response characteristics of the calculation program were tested by introducing artificially perturbed input temperature functions. The response to a spike or step disturbance was immediate; then the disturbance was damped out or a new equilibrium closely approached in 10 to 15 calculation time intervals.

The number of calculation time intervals required to attain convergence appears to vary with the abruptness and magnitude of the heat flux transient, the size and ratio (stability criterion) of the time and radius calculation intervals, and somewhat on the type of function and number of points used in determining the gradient at the wall from the calculated temperature distribution.

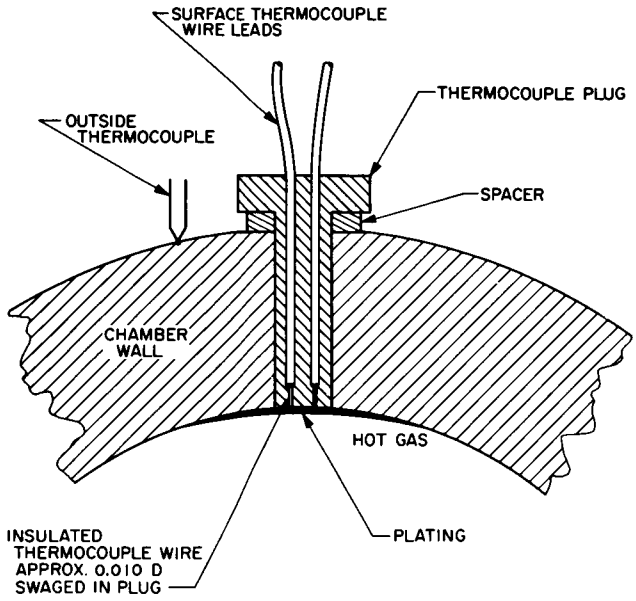

Figure 3. Surface thermocouple plug assembly.

Where the applied heat transfer varies irregularly, as it may in a rocket motor firing, the inner boundary temperature will not rise smoothly, and the radial temperature distribution profiles will reflect these perturbations. Under these conditions, the simple digital procedure may provide an adequate representation of the temperature gradient at the wall, with an accuracy consistent with that of the temperature measurements and the calculation of the interior temperature distribution.

EXPERIMENTAL TECHNIQUE

The essentials of the experimental technique are the method of measuring temperature on or close to the heat transfer surface and the means of recording this temperature at frequent intervals and in a form suitable for subsequent digital computations. The inner boundary temperature needed for the solution of equation (1) may be obtained by the use of a thermocouple plug, to be described. The outer boundary temperature is obtained by welding a thermocouple junction to the outside of the heat transfer body.

There are two types of thermocouple plugs: (1) the recessed type, which has the thermocouple positioned a short distance back from the heat transfer surface, and (2) the surface type, which has a thermocouple junction at the heat transfer surface itself. To minimize disturbance effects, the plugs are made of the same material as the heat transfer body.

Surface thermocouple plugs are readily installed and have been found to give good results. Furthermore, since the temperature extrapolation step in the calculation procedure is not needed, a source of error is eliminated and better results can be expected.

A typical surface thermocouple installation is shown in Figure 3. A commercially available plug,[1] having two separate, insulated, small-diameter thermocouple wires tightly swaged into holes drilled parallel to its axis, is pressed and clamped into a tightly fitting hole in the heat transfer body. The slightly projecting end of the plug is finished flush with the surrounding surface. Then a thin coat of metal is applied over the end of the plug and the adjacent surface area. This metal layer bridges the insulation around the thermocouple wires and bonds the ends of these wires to form a composite thermocouple junction. It should be the highest thermal conductivity metal which can be applied and which is compatible with the chemical and thermal environment. Also, it should be thick enough to smooth out the thermal disturbance caused by inserting the thermocouple wires into the body, thus maintaining the thermocouple junction at a temperature close to that of the surface of the undisturbed body material. However, too thick a surface layer will result in the thermocouple measuring a temperature which is somewhat lower than the undisturbed surface temperature, with a resultant error in the calculated heat flux.

In order to smooth out the thermal disturbance caused by insertion of the thermocouple into the body, the high-conductivity metal layer over the thermocouple wire clearly must have a thickness which is appreciable compared to the diameter of the thermocouple wire and its insulation. The upper limit of the plating thickness is established by the error in temperature and in calculated heat flux which can be tolerated. If one considers the effect of plating thickness alone, in the absence of temperature disturbance effects, it can be shown that for a heat flux of 6 Btu/in^2-sec a 0.002 nickel plating over a thermocouple junction on the surface of a steel body will cause the thermocouple to indicate a temperature which is 20 to 30 F lower than the true surface temperature, and that the heat flux calculated by using this measured temperature as the surface temperature will be approximately 1.25% less than the true surface heat flux. For the same conditions, but with a 0.004-in.-thick copper plate over a thermocouple junction on the surface of a copper body, the indicated temperature will be 4 to 6 F low and the calculated heat flux will be approximately 1% low. These considerations indicate that, with 0.010-in.-diameter thermocouple wires, and for heat flux up to approximately 10 Btu/in^2-sec, plating somewhat thicker than that mentioned above can be used to smooth out the temperature disturbance without introducing significant error into the temperature measurement or the calculated heat flux.

The metal layer is conveniently applied by electroplating. At least one commercial apparatus is available which enables an operator, by means of a hand-held swab, to plate a controlled thickness of almost any metal over a local region.[2] A further advantage of this procedure is that the thin plate can be applied, repaired, or replaced while the experimental equipment is in place in the test area, and without immersing the part.

[1]Advanced Technology Laboratories, Mountain View, California.
[2]Dalic Process. Sifco Metachemical, Inc., Cleveland 3, Ohio; Piddington and Associates, Limited, Pasadena, California.

The use of a high-speed digital data recording system greatly simplifies the subsequent handling of the thermocouple data and the calculation of the heat flux.[3] Thermocouple outputs can be amplified, digitalized, and recorded on magnetic tape which can be used directly as input to a computer. With this type of equipment it is possible to record thermocouple output and other data signals with repetition rates as low as 0.013 sec, which for many problems is satisfactory as a calculation mesh time increment. When shorter time increments are needed to maintain calculation stability with very small radial distance increments, linear interpolation between recorded data points is generally satisfactory.

APPLICATION OF METHOD IN ROCKET MOTOR TESTING PROGRAMS

Experimental rocket motor testing programs afford an opportunity to apply the aforementioned analytical and experimental techniques for the determination of heat transfer under non-steady-state conditions.

Short-duration (1- to 5-sec) rocket motor tests are used extensively in preliminary evaluation of liquid propellants. Such tests may be made with uncooled motors of any desired configuration. During the short firing time steady-state combustion is achieved, and both the propellant performance and the combustion stability of the system can be evaluated. The associated rapid heating of the uncooled chamber and nozzle walls creates conditions which make determination of local heat flux by the transient temperature measurement method feasible.

During the initial portion of each rocket motor test, the propellant flow rate is increasing, combustion is becoming established, and the heat transfer rate is increasing rapidly. The starting transient typically lasts from 0.25 to 0.50 sec. During this time the surface temperature of the chamber may rise from ambient to several hundred degrees Fahrenheit. At the end of the starting transient, the propellant mass flow and the combustion pressure and temperature are stabilized, and a fully established heat transfer process can be assumed to exist. From this point on the heat transfer rate decreases slowly, primarily because the continually increasing wall temperature decreases the driving potential for both convective and radiative heat transfer. The rate of decrease of heat flux with increase in wall temperature will also be affected by changes in the transport properties of the combustion product gases near the wall; no analytical method of predicting the magnitude of this variable physical property effect is available at present.

In a rocket motor, variation in heat flux with position on the motor wall can be expected as a result of nonuniform propellant injection or turbulence patterns within the chamber. These nonuniformities in heat flux will create transverse temperature gradients within the motor wall which will in turn affect the surface temperature of the mass of metal into which the heat from a local region on the surface is being conducted. The net effect will be to influence the surface temperature in such a direction that the computed heat flux will represent an average of the true heat flux at the point where the temperature is measured and the heat flux in adjacent regions. The effect of transverse heat conduction is absent at the start of a rocket motor test and increases with time as the transverse temperature gradients develop.

Because of the above considerations, it is desirable in rocket motor heat transfer testing to start the rocket motor as rapidly as possible, so that fully developed heat transfer conditions are achieved before: (1) the temperature disturbance has progressed far into the wall and transverse temperature differences have had an opportunity to become large, and (2) the surface temperature has reached the temperature of interest, i.e., the temperature at which the wall of a cooled motor would operate.

EXPERIMENTAL RESULTS

Three separate sets of rocket motor experimental data are summarized here to show the agreement of the thermocouple-plug-determined heat flux with calorimetrically-determined heat flux, and to demonstrate the sensitivity of the heat flux determination and the wide range of experimental conditions within which useful experimental heat transfer data can be obtained.

In one series of tests geometrically similar uncooled and sectional-water-cooled rocket motors (Figures 4 and 5) were operated with chlorine trifluoride–hydrazine propellant.[5] The propellant was injected into the combustion chamber through an injector having a number of cuplike elements distributed across its face.

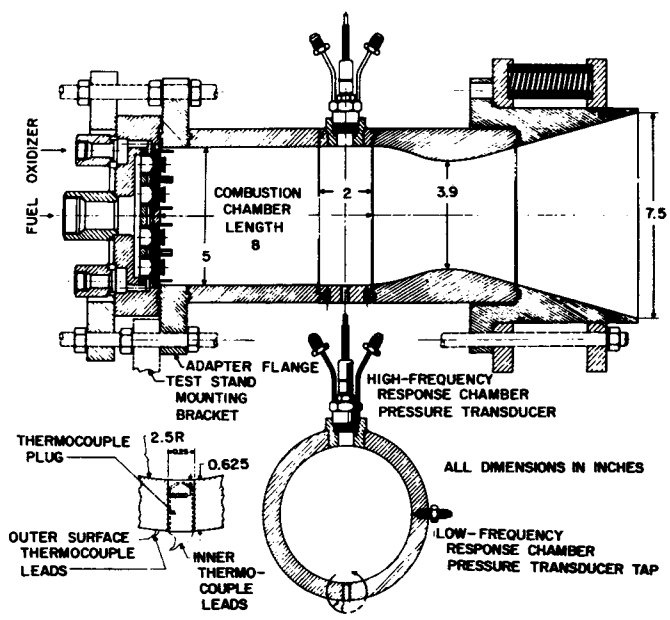

Figure 4. Uncooled thrust chamber assembly.

[3]Micro SADIC. Consolidated Systems Corporation, Pasadena, California.

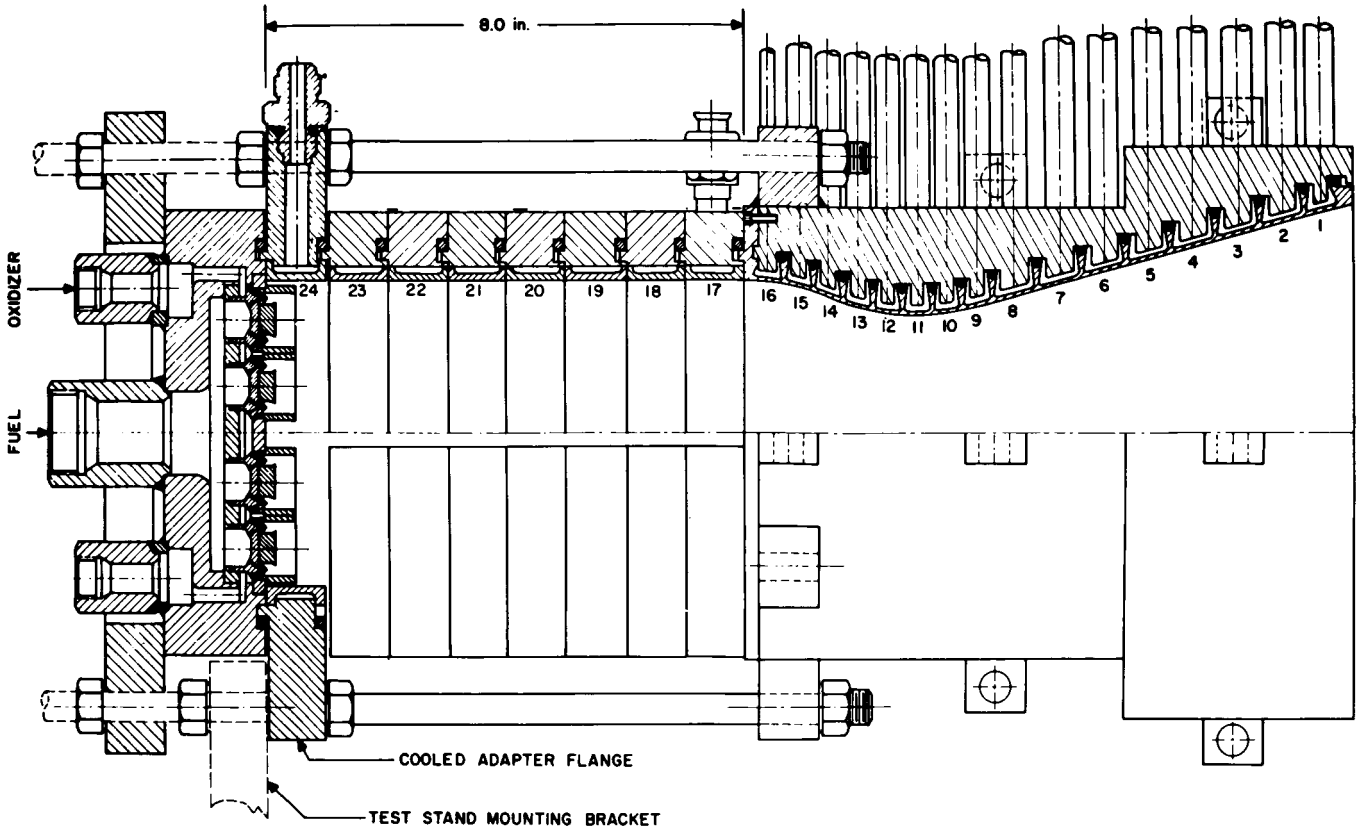

Figure 5. Sectional water-cooled thrust chamber assembly.

Streaking and erosion observed in the nozzle indicated that the propellant was not uniformly distributed circumferentially, and that the regions directly downstream of the injector elements experienced a higher heat transfer rate than the in-between regions.

The circumferential average heat transfer in the section of the combustion chamber just upstream of the nozzle is shown for a number of tests in Figure 6. This average was determined from calorimetric measurements made on the cooling water passing through that section of the cooled motor. Chamber sections having inner liners of stainless steel or of copper were used interchangeably. With the stainless steel liner the gas-side surface temperature was approximately 1100 F, while with the copper liner the gas-side temperature was approximately 400 F.

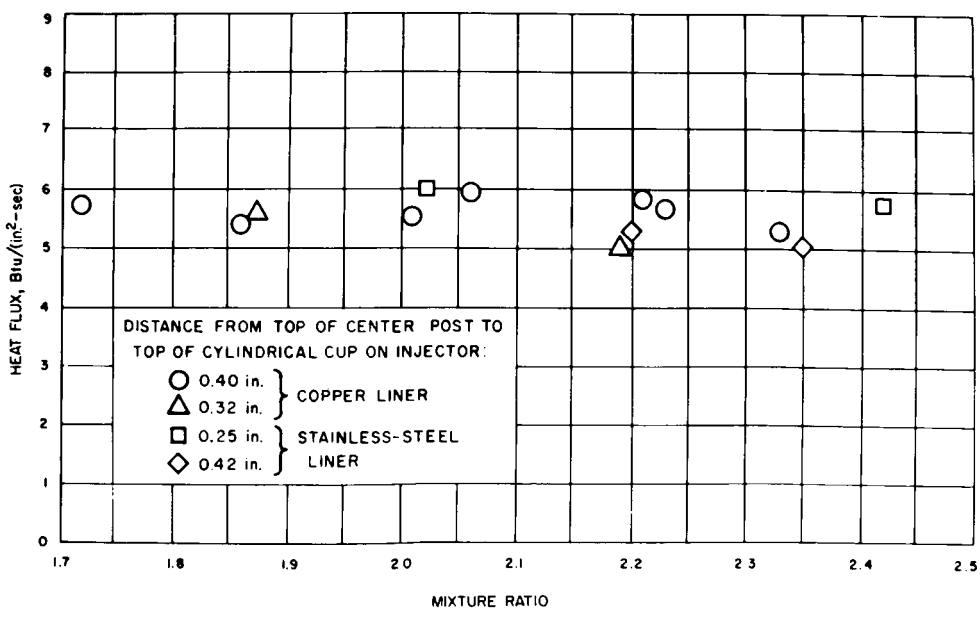

Figure 6. Average heat flux to section 17 of sectional water-cooled combustion chamber, 7 to 8 in. from injector face, using ClF_3–N_2H_4 propellant at approximately 300 psia chamber pressure.

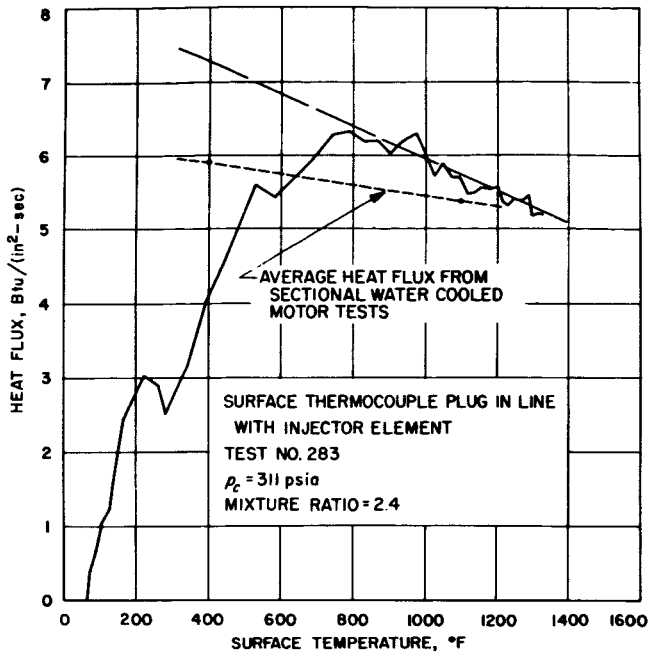

Figure 7. Local heat flux to combustion chamber of ClF_3–N_2H_4 rocket motor.

The uncooled motor had a thermocouple plug in its mild steel combustion chamber. The injector and the thermocouple plug section of the chamber could be rotated about the axis of the motor to adjust their relative orientation. A surface-thermocouple plug made of mild steel and having chromel and alumel thermocouple wires was used to obtain the data presented here. Nickel plate approximately 0.0005 in. thick was used to form the thermocouple junction.[4] Temperature was recorded every 0.013 sec, and this was also used as the calculation time interval. The thickness of the chamber wall was 0.625 in., and a radius increment of 0.025 in. was used for the heat transfer calculations.

Thermocouple-plug-derived heat flux for two angular positions of the thermocouple plug with respect to the injector elements is shown in Figures 7 and 8. Also shown for reference on these figures is a line indicating the average calorimetric heat transfer as a function of surface temperature for a corresponding section of the cooled chamber. It can be seen that the local heat flux is slightly higher than the circumferential average when the thermocouple plug is directly downstream of an injector element. When the thermocouple plug is aligned between injector elements the local heat flux is slightly less than the average heat flux. This comparison shows that the thermocouple-plug-computed heat flux is of the right magnitude compared to the calorimetric heat flux, and that local heat flux variations can be discerned.

In another test program, two rocket motors similar to those shown in Figures 4 and 5 were operated with nitrogen tetroxide–hydrazine propellant.[6] In this instance the uncooled motor had a mild steel nozzle with a constant wall thickness of 0.625 in. and with 15

[4]At the time the data shown on Figures 7 and 8 were obtained, a solution-deposition plating process was being used, and maximum plating thickness obtainable was approximately 0.0005 in.

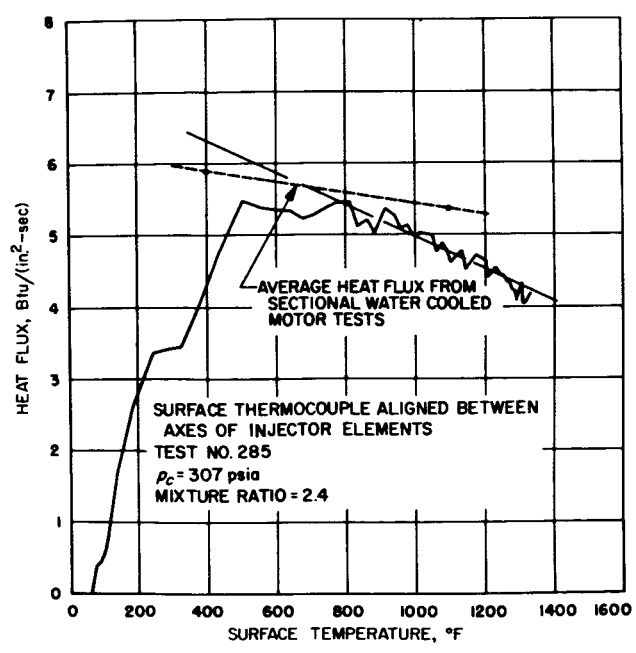

Figure 8. Local heat flux to combustion chamber of ClF_3–N_2H_4 rocket motor.

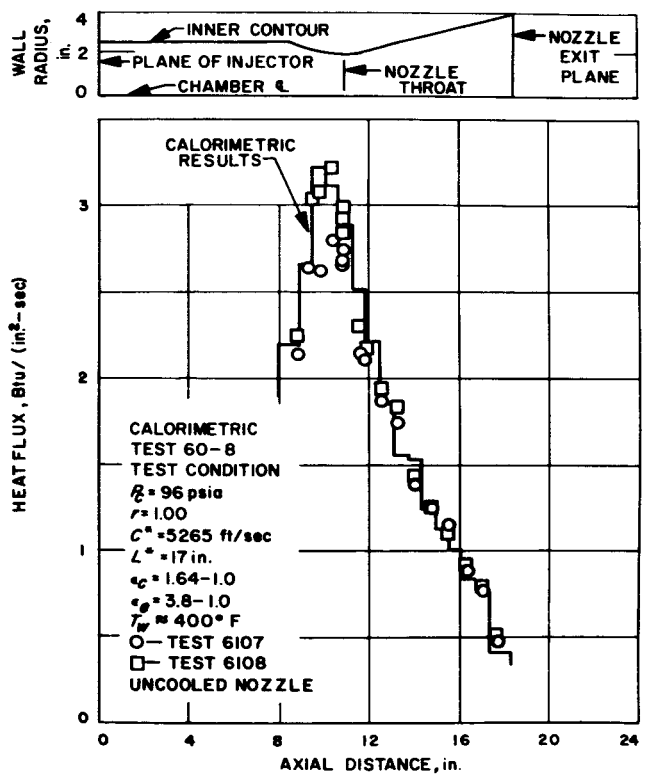

Figure 9. Comparison of sectional nozzle calorimetric average heat flux and local heat derived by thermocouple plug for nozzle of 1.64: contraction area ratio, using N_2O_4–N_2H_4 propellant at approximately 96 psia chamber pressure.

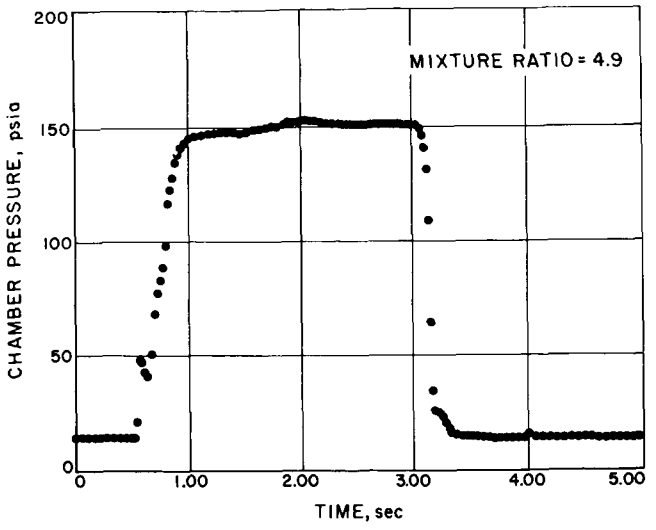

Figure 10. Development of chamber pressure in uncooled liquid-oxygen–liquid-hydrogen rocket motor.

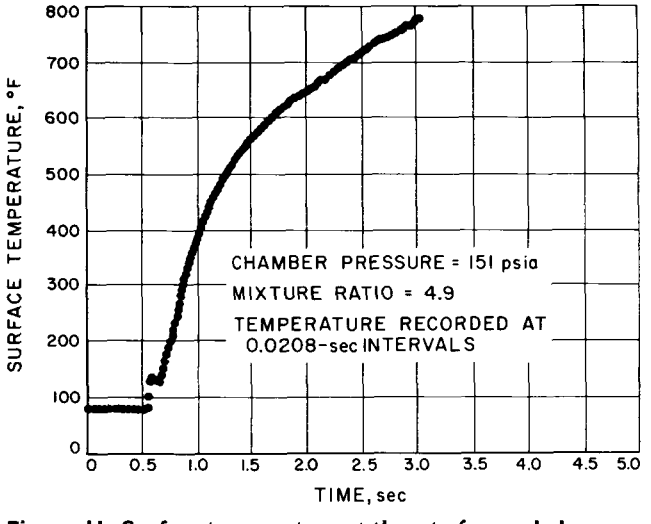

Figure 11. Surface temperature at throat of uncooled copper nozzle of liquid-oxygen–liquid-hydrogen rocket motor.

thermocouple plugs having junctions recessed 0.020 in. from the inside surface. The thermocouple plugs were distributed along the nozzle, some being in the converging section, some near the throat, and some in the diverging section. Figure 9 shows the comparison between the thermocouple plug heat flux and the calorimetric heat flux for various stations along the nozzle. In the computations, the effective cylindrical radius normal to the heat transfer surface was used. The good agreement indicates that the thermocouple plug method can be used to determine local heat flux in conical as well as cylindrical passages, and in the presence of moderate axial temperature gradients.

Performance and heat transfer data obtained from tests of an uncooled rocket motor having a copper exhaust nozzle and burning the liquid-oxygen–liquid-hydrogen propellant are shown in Figures 10, 11, 12, and 13. The chamber pressure record (Figure 10) shows that equilibrium propellant flow and fully developed combustion and heat transfer were not attained until almost 1.5 sec after operation was initiated. The copper nozzle had a 2-in.-thick wall in which eight copper thermocouple plugs, each containing a single constantan thermocouple wire, were installed. The copper plug itself was used as the other thermocouple lead. Copper plate approximately 0.005 in. thick was applied over the end of the thermocouple plug and the surrounding surface of the nozzle. The temperature measured by a thermocouple at the nozzle throat is given in Figure 11, and the corresponding computed heat flux is shown in Figures 12 and 13. The data of Figures 12 and 13 show a distinct change of slope at 2.0 sec (T_w = 650 F), corresponding to the establishment of steady-state flow conditions. These data show that the method is capable of following promptly variations in heat flux caused by gradual changes in combustion conditions.

The agreement between calorimetric heat flux and thermocouple-plug-determined heat flux indicates that

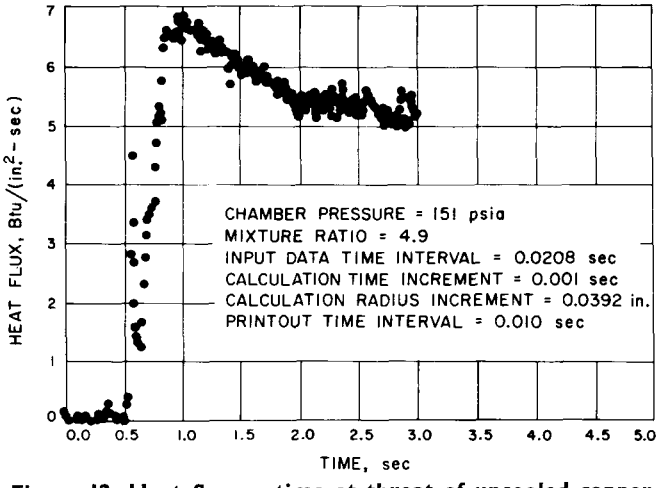

Figure 12. Heat flux *vs.* time at throat of uncooled copper nozzle of liquid-oxygen–liquid-hydrogen rocket motor.

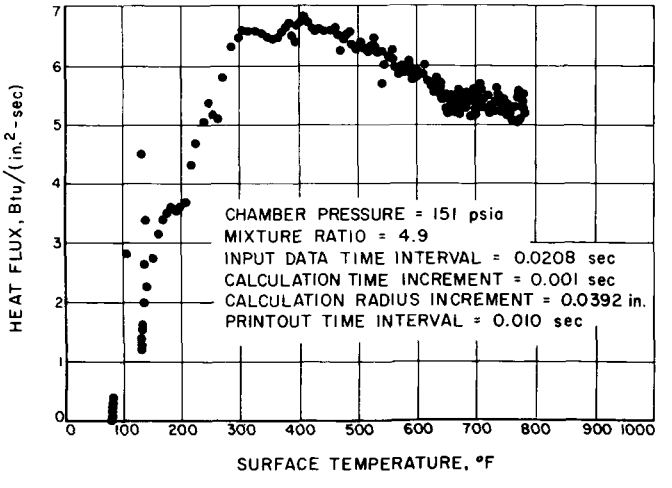

Figure 13. Heat flux *vs.* surface temperature at throat of uncooled copper nozzle of liquid-oxygen–liquid-hydrogen rocket motor.

the method described gives reasonable values of heat flux. However, the indicated variation of heat flux with wall temperature is sometimes considerably more than would be expected, particularly during the early part of a test. Possibly contributing to this effect are: (1) the temperature disturbance effect associated with insertion of the thermocouple wires into the body, (2) the deviation of the calculated heat flux from the correct value during the initial "convergence period" of the calculations, and (3) initial transients in the establishment of uniform propellant flow to and combustion in the rocket motor. Because of possible distortion in variation of heat flux with wall temperature, care should be taken in extrapolating test data in an effort to estimate heat flux at wall temperatures other than those existing during the "steady combustion" portion of a test.

CONCLUSIONS

The method described herein for computing heat flux from transient temperature measurements appears to be useful over a wide range of experimental conditions, despite the fact that in its derivation uniform heat transfer to the inside surface of a cylinder was assumed. As long as transverse temperature gradients are small compared to the radial temperature gradients used in determining the heat flux, good results can be expected. Heat flux in rocket nozzles having conical entrance and exit sections is also computed satisfactorily, using an effective cylindrical radius normal to the heat transfer surface.

The method is limited by the accuracy with which the internal temperature distribution can be calculated from the measured surface temperature data, and by the accuracy with which the temperature gradient at the surface can be determined from a curve fitted to this internal temperature distribution. In general, a certain number of calculation steps, and a corresponding number of calculation time intervals will be required after relatively steady-state heat transfer conditions have been established before accurate heat flux values will be given by the method described herein. The cumulative time interval, and the coincident surface temperature rise, will vary with the time increment used in the digital calculations. High-speed digital data recording equipment is needed to record the transient surface temperature at intervals of 0.020 sec or less if best results are to be obtained with the method.

If the heat flux and the calculation of the interior temperature distribution can be stabilized before the surface temperature has increased beyond the region of interest, and before transverse temperature gradients have had an opportunity to become large, then the method described herein should be useful in computing values of local heat flux.

NOTATION

c_p = Specific heat of material, function of temperature
k = Thermal conductivity of material, function of temperature
q = Heat flux to inner surface of cylinder
ρ = Density of material, function of temperature
r_j = Radial position in cylinder wall
r_0 = Radius of outside surface of cylinder
r_s = Radius of inside surface of cylinder
r_T = Radial position of inner thermocouple
Δ_r = Calculation interval, radius increment
Δ_t = Calculation interval, time increment
t_i = Time
T_0 = Initial uniform wall temperature
T_{t_i, r_j} = Temperature within wall as a function of time and radial position
T_{t_i, r_T} = Temperature measured at inner thermocouple position as function of time, boundary condition

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