COMPUTER PROGRAM TO CALCULATE
CONVECTIVE HEAT-TRANSFER COEFFICIENTS
FROM HARMONIC TEMPERATURE OSCILLATIONS

by Geraldine E. Amling and Ronald G. Huff

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1970
**Abstract**

Two FORTRAN IV version 13 programs are described which obtain the analytical solutions for convective heat-transfer coefficients related to either the phase lag or the amplitude ratio. The first, entitled BL, uses the ratio of the wall to driven hot fluid temperature to calculate the coefficients. The second, entitled JCL, uses the phase-lag angle between the sinusoidally driven fluid and wall temperature to calculate the heating fluid and coolant convective coefficients.

---

**Key Words**

- Computer program
- Heat-transfer coefficients
- Heat measurements
- Heat transmission
- Heat transfer
- Conductive heat transfer
- Convective heat transfer

**Distribution Statement**

Unclassified - unlimited

---

*For sale by the National Technical Information Service, Springfield, Virginia 22151*
COMPUTER PROGRAM TO CALCULATE CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE OSCILLATIONS

by Geraldine E. Amling and Ronald G. Huff

Lewis Research Center

SUMMARY

Two FORTRAN IV version 13 programs are described which obtain the analytical solutions for convective heat-transfer coefficients related to either the phase lag or the amplitude ratio. The first, entitled BL, uses the ratio of the wall to driven hot fluid temperature to calculate the coefficients. The second, entitled JCL, uses the phase-lag angle between the sinusoidally driven fluid and wall temperature to calculate the heating fluid and coolant convective coefficients. Criteria for the choice of either of the two methods and their mathematical formulation are described in detail in reference 1.

INTRODUCTION

The analytical expressions to determine the convective heat-transfer coefficients for a wall separating two fluids, one having an oscillating temperature, were derived in reference 1 from a second-order partial differential equation. These equations lead to computational procedures that are iterative and, therefore, time consuming and tedious. To alleviate this difficulty, two computer programs, BL and JCL, were written to provide the means for obtaining the numerical solutions to either the amplitude ratio or the phase-lag angle method quickly and accurately.

The data published in reference 1 were obtained by the use of these programs, and their descriptions and listings, which are shown herein, should prove helpful to anyone desiring to investigate further.

Specifically, the BL program calculates the convective heat-transfer coefficients related to the amplitude ratio for a plate separating two fluids, one of the fluids having an oscillating temperature. The JCL program, on the other hand, calculates the heat-transfer coefficients related to the phase lag.
STATEMENT OF THE PROBLEM

Figure 1(a) shows a wall that separates two moving fluids. The hot-gas-side fluid temperature $T_G$ is greater than the coolant temperature $T_C$, causing heat to flow through the wall in the positive $x$ direction. The problem is to determine the convective heat-transfer coefficients if either the hot-gas or coolant temperature is varied sinusoidally and if the temperature response of the wall is measured at only one point. Figure 1(b) shows what the wall temperature might look like at any given instant in time.

Figure 1. - Basic heat-transfer model.
METHOD OF ATTACK

If the hot-gas temperature is made to vary sinusoidally, the wall temperature will respond sinusoidally but will lag the driven temperature by an angle \( \phi \). In addition, the amplitude of the wall temperature oscillation will be less than that of the driven temperature. Both the phase lag \( \phi \) and the ratio of the amplitude of the wall temperature to the amplitude of the driven temperature \( \theta /\Delta T \) are, among other things, functions of the convective heat-transfer coefficients \( h \). Finding the relation between the convective heat-transfer coefficients and the phase lag \( \phi \), or the amplitude ratio \( \theta_m /\Delta T \), is required in order to solve for the coefficients.

To find this relation, the temperature response of the wall to a sinusoidally driven fluid temperature is derived. From this solution and steady-state heat-transfer conditions (which relate the ratio of the convective heat-transfer coefficients to the ratio of the temperature drops between fluids and wall), the absolute values of the coefficients can be determined as functions of either phase lag or amplitude ratio. The quantities that must be known as a function of time are the hot-gas temperature \( T_G \), the wall temperature at any point \( x \) \( (T(x, \tau)) \) and the coolant temperature \( T_C \). From these quantities either the phase lag or the amplitude ratio can be determined as well as the ratio of the convective heat-transfer coefficients. With the ratio of the coefficients, the frequency of the temperature oscillation, the wall material properties, and either \( \phi \) or \( \theta_m /\Delta T_G \), the convective heat-transfer coefficients \( h_G \) and \( h_C \) can be calculated.

It is also possible to calculate the coefficients by oscillating the coolant temperature sinusoidally. This approach requires the measurement of the same quantities as when the hot fluid temperature is oscillated.

The controlling differential equations and boundary conditions are given next. The one-dimensional transient heat-conduction equation

\[
\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial \tau} \tag{1}
\]

is solved for the temperature distribution in a wall that has convective heat transfer over its two surfaces (fig. 1). (Symbols are defined in the appendix.) The hot-gas side fluid temperature is driven sinusoidally and is given in equation form by

\[
T_G = \Delta T_G e^{-i\omega \tau} + T_G
\tag{2}
\]

All equations are numbered to correspond with those in reference 1.
where $T_G$ is given. It is not necessary to know the numerical value of $\Delta T_G$ if the phase lag is used for calculating the coefficients because the phase determination is independent of the absolute value of the temperature oscillation. If the amplitude ratio is used for calculating the coefficients, the $\Delta T_G$ must be computed from the change in chamber pressure. The boundary condition at the hot-gas side of the wall surface $x/L = 0$ equates the heat transferred by convection to that conducted away from the surface into the wall. This is given in equation form as

$$h_G [T_G - T(0, \tau)] = -K \frac{\partial T(0, \tau)}{\partial x}$$  \hfill (3)

The boundary condition at the coolant surface ($x/L = 1$) equates the heat conducted to the surface with the heat transferred convectively to the coolant. In equation form this is given by

$$h_c [T(L, \tau) - T_c] = \frac{K \partial T(L, \tau)}{\partial x}$$  \hfill (4)

The solution for the wall temperature as a function of time and location within the wall consists of the sum of the transient $\theta(x, \tau)$ and steady-state $T_s(x)$ solutions. The steady-state solution is found by setting $\partial T/\partial \tau$ equal to zero in equation (1) and assuming the wall temperature at $x/L = 0$ and 1 to be given as $T_{GW}$ and $T_{cw}$, respectively. This yields the usual linear temperature distribution with distance and can be written as

$$\bar{T}_s(x) = (\bar{T}_{cw} - \bar{T}_{GW}) \frac{x}{L} + \bar{T}_{GW}$$  \hfill (5)

The transient solution $\theta(x, \tau)$ is found by assuming the usual product solution: one a function of time only $F(\tau)$ and the other a function of the location within the wall measured from the heated side of the wall $X(x)$. Equations (1), (3), and (4) are modified to account for the change in variable from $T(x, \tau)$ to $\theta(x, \tau)$. The details of the solution of equation (1) using its pertinent boundary conditions (eqs. (2) to (4)) are shown in appendix B of reference 1.

The relation, derived from the steady-state (or mean) condition that requires the heat transferred convectively to the wall to equal the heat transferred convectively to the coolant, is expressed mathematically as
From the definition of $\psi$

$$h = \frac{K_M}{\psi} \quad (7)$$

The ratio of convective heat-transfer coefficients in equation (6) is defined as $R$. Calculating the ratio $R$ using equation (7) gives

$$R = \frac{\psi_G}{\psi_c} \quad (8)$$

where $R$ is also given by

$$R = \frac{T_G - T(0)}{T(L) - T_c} \quad (9)$$

The following assumptions have been used to obtain the solution:

(1) The heat flows through the plate in the $x$ direction only (one-dimensional heat conduction).

(2) The wall or plate properties (density, specific heat, and thermal conductivity) are constant.

(3) The convective heat-transfer coefficients on both sides of the wall are constant.

(4) The coolant temperature is constant.

The details of the analytical solutions are given in reference 1. However, the following equations are restated herein because they are used by the computer program to calculate the heat-transfer coefficients.

The equation involving amplitude ratio is

$$\frac{\delta_m}{\Delta T_G} = \frac{1}{\delta^2 + b^2} \left\{ \left( \frac{(\alpha a + \beta b)\cos \eta \pi x_L}{L} - \frac{(\alpha a + \beta b)\sin \eta \pi x_L}{L} \right)^2 \left[ \frac{\eta \pi L}{2} \right]^{x^2} \right\}^{1/2} \left( \eta \pi L \frac{2}{2} \right) \text{ (B37)}$$
where

\[
a = 1 - (\psi_G + \psi_c) + e^{2\eta L} \left[ (\psi_G + \psi_c + 2\psi_G\psi_c) \sin 2\eta L - (1 + \psi_c + \psi_G) \cos 2\eta L \right]
\]

(B28)

\[
b = (\psi_G + \psi_c - 2\psi_G\psi_c) + e^{2\eta L} \left[ (\psi_G + \psi_c + 2\psi_G\psi_c) \cos 2\eta L + (1 + \psi_c + \psi_G) \sin 2\eta L \right]
\]

(B29)

\[
c = (1 + \psi_c) \cos 2\eta L - \psi_c \sin 2\eta L
\]

(B30)

\[
d = \psi_c \cos 2\eta L + (1 + \psi_c) \sin 2\eta L
\]

(B31)

\[
e = 1 - \psi_c
\]

(B32)

\[
f = \psi_c
\]

(B33)

The equation involving phase lag angle is

\[
\psi_c^2 + \frac{[C + R(C + D)]}{R(F + G)} \psi_c^2 + \frac{2A + R(A + B)}{2R(F + G)} \psi_c + \frac{E}{2R(F + G)} = 0
\]

(B51)

where

\[
A = -\sin(\phi + \eta x) + e^{2\eta L} \cos(\phi + \eta x - 2\eta L) + e^{2\eta(2L-x)} \sin(\phi - \eta x)
\]

- \[e^{2\eta(L-x)} \cos(\phi - \eta x + 2\eta L)
\]

(B39)

\[
B = \cos(\phi + \eta x) - e^{2\eta L} \sin(\phi + \eta x - 2\eta L) - e^{2\eta(2L-x)} \cos(\phi - \eta x)
\]

+ \[e^{2\eta(L-x)} \sin(\phi - \eta x + 2\eta L)
\]

(B40)

\[
C = \sin(\phi + \eta x) + e^{2\eta L} \sin(\phi + \eta x - 2\eta L) + e^{2\eta(2L-x)} \sin(\phi - \eta x)
\]

+ \[e^{2\eta(L-x)} \sin(\phi - \eta x + 2\eta L)
\]

(B41)

\[
D = -\cos(\phi + \eta x) + e^{2\eta L} \cos(\phi + \eta x - 2\eta L) - e^{2\eta(2L-x)} \cos(\phi - \eta x)
\]

+ \[e^{2\eta(L-x)} \cos(\phi - \eta x + 2\eta L)
\]

(B42)
\[
E = \sin(\varphi + \eta x) - e^{2\eta L} \sin(\varphi + \eta x - 2\eta L) + e^{2\eta (2L-x)} \sin(\varphi - \eta x) \\
- e^{2\eta (L-x)} \sin(\varphi - \eta x + 2\eta L) \\
\]

\[
F = \cos(\varphi + \eta x) + e^{2\eta L} \sin(\varphi + \eta x - 2\eta L) - e^{2\eta (2L-x)} \cos(\varphi - \eta x) \\
- e^{2\eta (L-x)} \sin(\varphi - \eta x + 2\eta L) \\
\]

\[
G = -\sin(\varphi + \eta x) - e^{2\eta L} \cos(\varphi + \eta x - 2\eta L) + e^{2\eta (2L-x)} \sin(\varphi - \eta x) \\
+ e^{2\eta (L-x)} \cos(\varphi - \eta x + 2\eta L) \\
\]

The solution of this cubic equation can be obtained using the classical approach. The positive, nonzero, root will yield the desired convective heat-transfer parameter \( \psi_c \).

From equation (8), then

\[
\psi_G = R \psi_c \\
\]

Also, from equations (6) and (9), the following relation must be satisfied:

\[
R = \frac{h_c}{h_G} = \frac{T_G - T(0)}{T(L) - T_c} \quad (B49)
\]

DESCRIPTION OF BL AND JCL

The computer program, BL, was written to calculate the heat-transfer coefficients \( h_c \) and \( h_G \) by use of values of the thermal conductivity \( K \), the density of the wall material \( \rho \), the specific heat of the wall material \( c \), thickness of wall material \( L \), the ratio of distance measured from the heated surface wall to the thickness of the wall \( x/L \), the mean temperature of the hot gas \( T_G \), the wall temperature as a function of time at \( x = 0 \) \( T(0, \tau) \), the mean temperature of the coolant \( T_c \), the frequency of temperature oscillation \( f \), and the amplitude ratio \( \theta/\Delta T_G \).

The coolant wall temperature \( T_{cw} \) is initially set to a positive perturbation value in subroutine BALAN for the coolant temperature \( T_c \). The ratio of the convective heat-transfer coefficients \( R \) is then calculated, and with a linear relation of conductive heat transfer across the plate both heat-transfer coefficients \( h_c \) and \( h_G \) can be obtained. With these quantities, a calculated amplitude ratio is found and compared with the meas-
ured ratio. Then, by means of linear interpolation in subroutine BALAN, $T_{cw}$ is altered until the difference between the two ratios is less than $10^{-4}$.

It should be noted that the $\Delta T_{G}$ ratio as a function of the coolant wall temperature has a pole at $T(x, \tau)$ (fig. 2), which imposes a heavy restriction on the allowable error for the value of the amplitude ratio. If the error in the amplitude ratio exceeds 10 percent of the true value, the iteration will converge to a value for the coolant wall temperature in excess of the gas wall temperature.

The computer program JCL was written to calculate heat-transfer coefficients $h_c$ and $h_G$ by use of values of the thermal conductivity $K$, the density of wall material $\rho$, the specific heat of wall material $c$, thickness of wall material $L$, the ratio of distance measured from the heated surface of the wall to the thickness of the wall $x/L$, the mean temperature of the hot gas $T_G$, the wall temperature as a function of distance (measured into wall from hot surface) $T(x, \tau)$, the mean temperature of the coolant $T_c$, the frequency of temperature oscillation $f$, and the phase lag angle $\theta$. The coolant wall temperature $T_{cw}$ is initially set to equal the measured temperature of the wall $T(x, \tau)$. The ratio $R$, of the convective heat-transfer coefficients is calculated, and the coolant wall temperature value is corrected for the wall temperature drop due to conduction. Only the positive, nonzero root is used when solving the cubic equation.

Figure 2. - Typical variation of amplitude ratio versus coolant wall temperature $T_{cw}$ showing singularity at $T_{cw} = T_{GW}$.
These programs assume that the hot-gas-side temperature is measured. Therefore, the coolant wall temperature is calculated from the following equation:

\[ T_{cw} = T(x, \tau) - \frac{(h_G)(L)}{K} \left( T_G - T(x, \tau) \right) \]

If the wall temperature is measured at a point other than the hot-gas surface \( x/L \approx 0 \), the programs must be modified to account for the new location.

**INPUT CARDS**

**Program BL**

The BL program requires the following cards for input information:

Card 1: Three values with 312 format (table I, line 1) containing
- IRDG: reading number
- ETA: station number
- NR: number of readings to be processed

Card 2: Nine values with 10E8.4 format (table I, line 2) containing
- K: conductivity
- RHO: density of wall material
- CC: specific heat of wall material
- L: thickness of wall material
- XL: ratio of distance measured from hot-gas side of wall and temperature measuring location to wall thickness
- TG: mean temperature of hot gas
- TWO: wall temperature, a function of time, at \( x = 0 \)
- TWL: wall temperature, a function of time, at \( x = L \)
- TC: mean temperature of coolant

Card 3: Contains pairs of values (table I, line 3) under 10E8.4 format showing
- WRAD(1): frequency of temperature oscillation
- OMDTG(1): ratio of amplitude of wall temperature oscillation to amplitude of sinusoidally driven hot-gas temperature
The program read in $NR$ pairs of values, up to five pairs in card 3. If more than five pairs are desired, more cards may be added. The NR pairs will continue to be read under the same 10E8.4 format.

<table>
<thead>
<tr>
<th>Line</th>
<th>Station Number</th>
<th>ForTRAN Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.0700-0</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.1970-0</td>
<td>0.3550</td>
</tr>
</tbody>
</table>

**Program JCL**

The JCL program requires the following cards for input information:

**Card 1:** Three values with 3I2 format (table II, line 1) containing
- IRDG  reading number
- ISTA  station number
- NR    number of readings to be processed

**Card 2:** Eight values with 10E8.4 format (table II, line 2) containing
- K     conductivity
- RHO   density of wall material
- CC    specific heat of wall material
- L     thickness of wall material
- XL    ratio of distance measured from hot-gas side of wall and temperature measuring location to wall thickness
- TG    mean temperature of hot gas
- TGW   wall temperature, a function of distance
- TC    mean temperature of the coolant

**Card 3:** Contains pairs of values (table II, line 3) under 10E8.4 format showing
- WRADA(1) frequency of temperature oscillation
- PHIRA(1) phase lag angle between driving gas temperature and responding wall temperature
The program reads in NR pairs of values up to five pairs in card 3. If more than five pairs are desired, more cards may be added. The NR pairs will continue to be read under the same 10E8.4 format.

**TABLE II. - SAMPLE INPUT FOR PROGRAM JCL**

| FORTRAN STATEMENT | 
|-------------------|-----------------|-----------------|-----------------|
| 1 1 1             | 2.2070 .3600+0 | 1.1700 .6000+0 | 1.1867+0 .9600+3 .6580+3 .5706+3 |
| 3 .1970 .043965+1 | 

**OUTPUT**

The outputs of both BL and JCL programs display the descriptive title followed by a list of the input values with their program labels. The results of the calculations appear under the heading OUTPUT shown in the next sections.

**Program BL**

**TCWA**  calculated coolant wall temperature  
**TEST1**  heat flux to coolant  
**TEST2**  heat flux from hot gas  
**TEST**  ratio of heat flux to coolant to heat flux from hot gas (ideally should be 1.0)  
**HCT**  time averaged convective heat-transfer coefficient on coolant side of wall  
**HGT**  time averaged convective heat-transfer coefficient on hot-gas side of wall  
**ERROR**  (1.0 - TEST) which is used by the program to test against the convergence criterion  
**R**  ratio of convective heat-transfer coefficients  
**THETA**  final calculated value of ratio of the amplitude of wall temperature to amplitude of sinusoidally driven hot-gas temperature
Program JCL

TCW  calculated coolant wall temperature
TEST1 heat flux to coolant
TEST2 heat flux from hot gas
TEST  ratio of heat flux to coolant to heat flux from hot gas (ideally should be 1.0)
HCT  time averaged convective heat-transfer coefficient on coolant side of wall
HGT  time averaged convective heat-transfer coefficient on hot gas side of wall
ERROR (1.0 - TEST) which is used by the program to test against convergence criterion
R  ratio of convective heat-transfer coefficients
PSIC convective heat-transfer parameter on coolant side of wall
PSIG convective heat-transfer parameter on hot-gas side of wall
GR  check on the zero of eq. (B51) which should be equal to 0.0000

COMPUTER PROGRAMS

These programs are written in FORTRAN IV and are operational on the IBM 7094-2/7044 direct-coupled system of the Lewis Research Center. Program BL uses approximately 5187 storages and Program JCL uses approximately 4261 storages. Flow charts of the programs are shown in figures 3 and 4.

Machine running time for both programs is minimal, each using less than 1 minute per case.
PROGRAM BL - AMPLITUDE RATIO GIVEN

Figure 3. - Flow chart for program BL.
Program BL - Amplitude Ratio Given

Parameters $$(1, X, Y)$$

SUBROUTINE BALAN

PARAMETERS (1, X, Y)

/ BALAN /

2.03

EXECUTE GO TO

1 AT 3.03

2 AT 3.03

EXECUTE

FALSE

ABS(Y) .LT. 1.E-4

TRUE

X = 15

V

B

X = (2-X1+Y2-V1) * 1 (V1) * X1

V1 = Y2

= 9

EXIT

***

FIGURE 3. - Concluded.

Program BL

---

CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE Oscillations - Amplitude Ratio Given

NR = Number of readings to be computed

K = Thermal conductivity of Wall Material

RHO = Density of Wall Material

CC = Specific heat of Wall Material

15
L = thickness of wall material
XL = ratio of distance measured from HCT gas side of the wall
temperature measuring location to wall thickness
TC = mean temperature of HCT gas
Tw = wall temperature, function of time, X = 0.0
Tl = wall temperature, function of time, X = L
WRAD = frequency of temperature oscillations
OMDTG = ratio of the amplitude of the wall temperature to the amplitude of the sinusoidally driven HCT gas temperature
ALPFC = thermal diffusivity
ETA = frequency and wall property parameter
HCA(1) = lower limit of coolant side convective heat-transfer coefficient
HCA(2) = upper limit of coolant side convective heat-transfer coefficient
FC = time averaged convective heat-transfer coefficient
N = coolant side of the wall
HT = time averaged convective heat-transfer coefficient at HCT gas side of the wall
IK = number of iterations
R = ratio of convective heat-transfer coefficients
TCWA = calculated coolant wall temperature
TEST1 = heat flux to the coolant
TEST2 = heat flux from the HCT gas

C*******************************************************************************
C DIMENSION TCWA(300),WRAD(300),OMDTG(300),HCA(4),THETA(4)
C EQUIVALENCE (PSIC,PHIC),(PSIG,PHIG)
C REAL K,L,NLMI,NLMB,NUM,NEWERR
C*******************************************************************************
C REAC INPUT
C*******************************************************************************
1 REAC(5,10C) IRDG,ISTA,NR
   REAC(5,10I) K,RHO,CC,XL,TG,TL,TL,TC
   REAC(5,10I) (WRAD(I),OMDTG(I),I=1,NR)
C*******************************************************************************
C PRINT TITLE AND INPUT
C*******************************************************************************
WRITE (6,102)
WRITE(6,143) IRDG,ISTA
ALPFC=K/(RHO*CC)
DO 2 J=1,NR
WRITE(6,144) I
WRITE(6,145) I
WRITE(6,147) K,RHO,CC,XL,TG,TL,TL,TC,WRAD(I),OMDTG(I)
C*******************************************************************************
C INITIALIZE STARTING VALUES FOR ITERATION
C*******************************************************************************
TG=Tw
TC=TC+10.
IGO=1
C*******************************************************************************
C DEFINE HCT BOUNDARY CONDITIONS AND CALCULATE R RATIO
C*******************************************************************************
      R=(TG-TCWA)/(TCwa-TC)
      TG=K*(TCwa-TG)/(L*(TG-TCWA))
      TC=R*TC
C***************************************************************************************
C CALCULATE AND COMPARE AMPLITUDE RATIOS
C***************************************************************************************
ETA=SQR(T(θRAD(I)/(2.0*ALPHA1))
ETAL=ETA*A*L
ANG=2.0*EAL
SING=ΣN(ANG)
CNG=CCS(ANG)
EXPANG=EXP(ANG)
TFETA(I)=CMDTG(I)
ANG1=ETAL*X*L
EXP1=EXP(ANG1)
ANG2=ETAL*(2.0-C-XL)
EXP2=EXP(ANG2)
CS1=CCS(ANG1)
SIN1=ΣIN(ANG1)
PFI1=K*ETA/H*C
PFI1=R*PH1C
PGPCC=PH1C*PHIC
PGPCC2=PH1C*PHIC*2.0
F=PFI1
E=1.0-F
PCP1=PFI1+1.0
D=F*CANG+PCP1*SANG
C=PCP1*CANG-PHIC*SANG
B=PGPCC-PGPC2*X*EXPANG*PGPCC+PGPC2*CANG
A=1.0-PGPPC*EXPANG*PGPCC+PGPC2*CANG
DEL1=C*A-C*B
CEL2=C*A*C*B
CEL3=F*A-E*B
CEL4=E*A+F*B
NUM1=(CEL1*SIN1-DEL2*CPS1)*EXP2
NUM2=(CEL2*COS1-DEL4*SIN1)*EXP1
NUM3=NUM2-NUM1
DEN=(CEL4*COS1+DEL3*SIN1)*EXP1-(DEL1*CPS1+DEL2*SIN1)*EXP2
A2PB2=A++2+B++2
CON=SQR(T(NUM**2+DEN**2)
AMPTG=CON/A2PB2
DIFF=AMPTG-OMDTG(I)
CALL EALAN( TC*, IGC; DIFF)
IF( IGC.LT.10) GO TO 9
IJK=1
TCW( IJK ) = TCW
FCL=+C
FGT=+C
TFETA(I)=AMPTG
TEST1=FCL*(TG-TG)
TEST2=FCL*(TG-TG)
TEST=TEST1/TEST2
ERROR=1.0-TEST
C*****************************************************************************
C PRINT OUTPLT
C*****************************************************************************
WRITE(6,1CS)
WRITE(6,1IC)
WRITE(6,111) TCW( IJK ); TEST1, TEST2, TEST, HCT, HGT, ERRCR, R, THETA(4)
END
C  FORMAT STATEMENTS
C*********************************************************************************
10C FORMAT(2I2)
1CI FORMAT(100E.4)
1C2 FORMAT(12CH+CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE OSCILLATIONS - AMPLITUDE RATIO GIVEN )
1C3 FORMAT(18F+READING NUMBER = ,I2,10X,18H STATION NUMBER = ,I2)
1C4 FORMAT(4HCRUN,12)
1C5 FORMAT(6H(INPLT))
1C6 FORMAT(1HC,4X,1HK,8X,3HRHC,8X,2HCC,8X,1HL,9X,2HXL,8X,2HTG,7X,3HTWO
1,7X,3H1ML,7X,2H1C,7X,4HWRAD,6X,5HCMDTG)
1C7 FORMAT(1HC,F8.6,4F10.4,4F1C.1,2F10.4)
1C8 FORMAT(5F+ITERATIONS EXCEED 5C )
1C9 FORMAT(7HCOLTPL1)
110 FORMAT(1HC,3X,4HTCW,A,5X,5HTEST1,5X,5HTEST2,6X,4HTEST,6X,3HTCT,7X,3
1HGT,6X,5FERROR,7X,1HR,7X,5HTHE1A)
111 FORMAT(1HC,F8.1,3F10.4,2F1C.6,3F10.4)
112 FORMAT(5F+CSOLUTION IS DIVERGING )
END

### LEFT BALAN

SUBROUTINE BALAN(X,K,Y)
GO TO (1,2),K
1 X1=X
Y1=Y
X=X*X/10.
K=2
RETURN
2 X2=X
Y2=Y
IF(ABS(Y).LT.1.E-4)K=15
X=(X2-Y1)/(Y2-Y1)*(-Y1)+X1
X1=X2
Y1=Y2
RETURN
END

---

Program BL Output

CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE OSCILLATIONS - AMPLITUDE RATIO GIVEN
READING NUMBER = 1  STATION NUMBER = 1
RUN 1
INPUT
K  RHO  CC  L  XL  TG  TWO  TML  TC  WRAD  CMDTG
0.00620  1.2860  0.1170  0.0600  0.1667  960.0  658.0  658.0  976.6  1.2390  0.1538
OUTPUT
TCW  A  TEST1  TEST2  TEST  HCT  HGT  ERRCR  R  THE1A
6.15 0.1344  0.1344  0.9998  0.002775  0.000045  0.0002  6.235C  0.1538
*01* UNITS=C, EOF.
REC= CC00C FILE= 00002
Figure 4 - Flow chart for program JCL
Figure 4. - Continued.
Figure 4 - Continued.
Figure 4. - Continued.
Figure 4. - Continued.
Figure 4. - Continued.
Figure 4. - Continued.
Figure 4. Concluded.
Program JCL

$IEFIC JCL

C
C******************************************************************************
C CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE
C OSCILLATIONS - PHASE LAG ANGLE GIVEN
C******************************************************************************
C
C IRDG=READING NUMBER
C ISTA=STATION NUMBER
C     NR=NUMBER OF DATA POINTS TO BE COMPUTED
C     K=THERMAL CONDUCTIVITY OF WALL MATERIAL
C     RH0=DENSITY OF WALL MATERIAL
C     CC=SPECIFIC HEAT OF WALL MATERIAL
C     L=THICKNESS OF WALL MATERIAL
C     XL=RATIO OF DISTANCE MEASURED FROM HOT GAS SIDE OF THE WALL
C     TEMPERATURE MEASURING LOCATION TO WALL THICKNESS
C     TG=MEAN TEMPERATURE OF HOT GAS
C     TG=MEAN TEMPERATURE FUNCTION OF DISTANCE
C     TC=MEAN TEMPERATURE OF THE COOLANT
C     WRIA=PHASE LAG FREQUENCY OF TEMPERATURE OSCILLATIONS
C     PHIRA=PHASE LAG ANGLE BETWEEN THE DRIVING GAS TEMPERATURE AND THE
C     RESPONDING WALL TEMPERATURE
C     ALPHA=THERMAL DIFFUSIVITY
C     ETA=FREQUENCY AND WALL PROPERTY PARAMETER
C     CR=CUBIC EQUATION CHECK OF RCCTS, SHOULD APPROXIMATE ZERC
C     FCT=TIME AVERAGED CONVECTIVE HEAT-TRANSFER COEFFICIENT ON
C     COOLANT SIDE OF THE WALL
C     FCT=TIME AVERAGED CONVECTIVE HEAT-TRANSFER COEFFICIENT ON HOT
C     GAS SIDE OF THE WALL
C     IJK=NUMBER OF ITERATIONS
C     R=RATIO OF CONVECTIVE HEAT-TRANSFER COEFFICIENTS
C     PSIG=CONVECTIVE HEAT-TRANSFER PARAMETER ON THE HOT GAS SIDE OF
C     THE WALL
C     PSIC=CONVECTIVE HEAT-TRANSFER PARAMETER ON THE COOLANT SIDE OF
C     THE WALL
C     TCV=CALCULATED COOLANT WALL TEMPERATURE
C     TEST1=HEAT FLUX TO THE COOLANT
C     TEST2=HEAT FLUX FROM THE HOT GAS
C     CONV=CONVERGENCE CRITERION USED FOR EACH ROOT
C
C******************************************************************************
C
DIMENSION WRADA(100),PHIRA(100),TCWA(100),Z4(4),CCNV(4)
REAL L,K
DATA CRITN/.1.E-5/
PI=3.1415926
PI018C=PI/180.
C******************************************************************************
C REAC INPUT
C******************************************************************************
1 REAC(5,100) IRDG,ISTA,NR
   REAC(5,101) K,RH0,CC,L,XL,TG,TGK,TC
READ(5,1C1) (WRADA(I), PHIRA(I), I=1, NR)
C*******************************************************************************
C PRINT TITLE AND INPUT
C*******************************************************************************
WRITE (6,102)
WRITE(6,1C3) IRDG, ISTA
DO 5 JJ=1, NR
WRITE(6,1C4) JJ
WRITE(6,1C5)
WRITE(6,1C6)
WRITE(6,1C7) K, RHO, CC, L, XL, TG, TGA, TC, WRADA(JJ), PHIRA(JJ)
C*******************************************************************************
C INITIALIZE STARTING VALUES FOR ITERATION
C*******************************************************************************
   IJK=1
   TCWA(IJK)=TGW
   TCW=TCW
   WRAC=WRADA(JJ)
   PH1=PHIRA(JJ)
C*******************************************************************************
C CALCULATE R RATIO
C*******************************************************************************
   R=(TG-TGW)/(TCW-TC)
   ALPFA=K/(RHO*CC)
   X=L*XL
   ETA=SQRT(WRAD/(2.0*ALPHA))
   ETAL=ETA*L
   ETAL2=ETAL*2.0
   ETAX=ETAL*XL
   ANG1=PH1+ETAX
   SIN1=Sin(ANG1)
   COS1=Cos(ANG1)
   ANG2=ANG1-ETAL2
   SIN2=Sin(ANG2)
   COS2=Cos(ANG2)
   ANG3=PH1-ETAX
   SIN3=Sin(ANG3)
   COS3=Cos(ANG3)
   ANG4=ANG3+ETAL2
   SIN4=Sin(ANG4)
   COS4=Cos(ANG4)
   EXP1=EXP(ETAL2)
   EXP2=EXP(ETAL2*(2.0-XL))
   EXP3=EXP(ETAL2*(1.0-XL))
   A=-SIN1+EXP1*Cos2+EXP2*SIN3-EXP3*COS4
   B=COS1-EXP1*SIN2-EXP2*COS3+EXP3*SIN4
   C=SIN1+EXP1*SIN2+EXP2*SIN3+EXP3*SIN4
   D=-COS1+EXP1*Cos2-EXP2*COS3+EXP3*COS4
   E=SIN1-EXP1*SIN2+EXP2*SIN3-EXP3*SIN4
   F=COS1+EXP1*SIN2-EXP2*COS3-EXP3*SIN4
   G=-SIN1-EXP1*Cos2+EXP2*SIN3+EXP3*COS4
C*******************************************************************************
C SOLVE FOR ROOTS OF CUBIC EQUATION
C*******************************************************************************
   Z(3)=(C*R*(C+D))/(R*(F+G))
   Z(2)=(2.0*A+R*(A+B))/(2.0*R*(F+G))
   Z(1)=E/(2.0*R*(F+G))
   Z(4)=1.0
   AA(2)=Z(3)

30
AA(2)=Z(1)
AA(4)=Z(2)
AA(1)=1,00C
DO 6 KK=1,3
6 CONV(KK)=CRTRN
N=3
CALL R POLY(N,AA,50,1.E-7,LU,YY,CCNV,HH,EB,CCC,CC,EE)
C********************************************************************
C Suppliers of positive real root
C******************************************************************************
KOUT=C
DO 7 K1=1,3
IF(VV(KT).NE.0.00) GO TO 7
KK=KT
KOUT=KOUT+1
7 CONTINUE
IF(KOUT.EQ.1) GO TO 11
KOUT=C
DO 9 K1=1,3
IF(UU(KT).LE.C,00) GO TO 9
KK=KT
KOUT=KOUT+1
9 CONTINUE
IF(KOUT.EQ.1) GO TO 12
10 WRITE(6,112) NR
GO TO 5
11 IF(UU(KK).LE.0,00) GO TO 10
12 REAL2=LL(KK)
   REAL1=REAL2*R
   GR=((REAL2*Z(2))*REAL2+Z(2))*REAL2+Z(1)
   HCT=(K*ETA)/REAL2
   G1=(K*ETA)/REAL1
   PSIC=REAL2
   PSIC=REAL1
C******************************************************************************
C Calculate and compare coolant wall temperatures
C******************************************************************************
IJK=IJK+1
TCWA(IJK)=TCW-TGT*(TG-TGW)/K
TCW=TCWA(IJK)
TEST1=TGT*(TC-W-TC)
TEST2=TGT*(TG-TGW)
TEST=TEST1/TEST2
ERROR=1.0-TEST
IF(ABS(ERROR).LT.0.01) GO TO 4
TCWA(IJK)=(TCWA(IJK-1)+TCWA(IJK))/2.0
TCW=TCWA(IJK)
IF(IJK.EQ.50) GO TO 2
WRITE(6,113) NR
GO TO 5
4 R=(TG-TGW)/(TC-W-TC)
C******************************************************************************
C Print output
C******************************************************************************
WRITE(6,114) NR
WRITE(6,110)
WRITE(*,111) TBA(IJK),TEST1,TEST2,TEST,HCT,HGT,ERRCR,R,PS IC,PS SIG,
1 GR
5 CONTINUE
WRITE(*,114)
GO TO 1
C FORMAT STATEMENTS
C******************************************************************************
C FORMAT(212)
 IC FORMAT(10OE,4)
 IC FORMAT(12CH,CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATORE OSCILLATIONS - PHASE LAG ANGLE GIVEN )
 IC FORMAT(18H,CREADING NUMBER = I2,10X,18H STATION NUMBER = I2)
 IC FORMAT(4HCRUN,I2)
 IC FORMAT(6HCINPUT)
 IC FORMAT(1HC,4X,1HK,8X,3HRHC,E8,2HGC,8X,1HL,9X,2HXL,8X,2HTG,7X,3HTGW
 1,8X,2HTC,6X,5HRADA,5X,5HPHIRA)
 TC FORMAT(1HC,F8.6,4F10.4,3F1C.1,2F10.4)
 TC FORMAT(55HITERATIONS EXCEED 50)
 TC FORMAT(7HCOUTPUT)
 TC FORMAT(1HC,4X,3HTC,5X,5HTEST1,5X,5HTEST2,6X,4HTEST,6X,3HHC,7X,3H
 1HTG,6X,5HERKOR,7X,1HR,8X,4HPSIC,6X,4HPSIG,7X,2HGR)
 TC FORMAT(1HC,F8.1,3F10.4,2F10.6,5F10.4)
 TC FORMAT(40HCERROR IN SUBR RTPOLY FOR DATA POINT NO. 15)
 TC FORMAT(63HQA UNIQUE POSITIVE REAL RCCT CANNOT BE FOUND FOR DATA PO
 1 INT NO. 15)
 TC FORMAT(1HC1)
END
$IEFT POLR
SUBROUTINE RTPOLY(N,A,L,F,U,V,CCNV,H,B,C,D,E)
C ORDER OF INPUT POLYNOMIAL
C COEFFICIENTS OF INPUT POLYNOMIAL IN DESCENDING ORDER
C MAXIMUM NUMBER OF ITERATION FOR EACH RCCT
C DESIRED TOLERANCE (REMAINDER / CONSTANT TERM)
C REAL PART OF ROOT
C IMAGINARY PART OF RCCT
C CONVERGENCE CRITERION USED FOR EACH ROOT
C IF AFTER L ITERATIONS CONVERGENCE WITHIN F FAILS, THE TOLERANCE IS RELAXED BY 10.
C WORKING STORAGE
C WORKING STORAGE
C WORKING STORAGE
C WORKING STORAGE
C WORKING STORAGE
C DIMENSION A(40),U(40),V(40),CCNV(40),H(40),B(40),C(40),E(40)IB40016C
C DOUBLE PRECISION A,U,V,H,B,C,D,E
C COUPLE PRECISION P,Q,R,S,PS,CS,PT,QT,HH,HNL,XX,SS,SSSS
C NSAVE = N
C IV = N+1
C DO 1 I = 1,NN
1 H(I) = A(I)
C EXTRACT ZERO ROOTS
2 IF(h(NH)) 4,3,4
3 U(N) = C.
4 V(N) = C.
C CONV(N) = X
C N = N-1
C 32
NN = N + 1
GO TO 7
4 IF(N) 500,500,10
C INITIALIZE P,Q,ETC.
1C S = C.
PS = C.
QS = C.
PT = C.
QT = 0.
XK = F.
IF (N-1) 500,12,20
12 R = -(2)/H(1)
GO TO 10C.
2C NN = N + 1
C SCALE COEFFICIENTS OF POLYNOMIAL.
I=0
DO 2C J = 1,NN
IF(H(J)) 24,30,24
24 I=I+LOG2(H(J))
30 CONTINUE
FN = N + 1
S = 5**((1/NN))
DO 32 J = 1,NN
32 H(J) = S(J)*S
IF(DABS(H(1)/H(1)) - DABS(H(H)/H(NN))) 34,40,40
C REPLACE X BY (1/X)
34 LT = - LT
M = NN/2
DO 36 J = 1, M
H(J) = H(J)
MNN =N+2-J
H(J) = H(MNN)
36 H(MNN) = H(J)
4C IF(QS) 42,44,42
42 P = PS
Q = QS
GO TO 54
44 IF(N-1)) 46,46,48
46 Q = 1.
P = -2.
GO TO 50
48 Q = H(NN)/H(N-1)
59S P = (F(N)-H(N-2)*Q)/H(N-1)
5C IF(Z-N) 52,199,4
52 R = C.
C BEGIN ITERATIONS
54 I = 0
C BAIRSTICK ITERATION
6C B(1) = H(1)
C(1) = B(1)
B(2) = H(2) - B(1)*P
C(2) = B(2) - C(1)*P
DO 62 J = 3,NN
B(J) = H(J) - B(J-1)*P - B(J-2)*C
62 C(J) = B(J) - C(J-1)*P - C(J-2)*C
IF(B(N)) 162,64,162
162 HN1 = H(N) - B(N-2)*Q
IF(H(N1)) 164,166,166
164 IF(XK - DABS(B(N)/HN1)) 70,7C,64
166 IF(H(N)) 168,17C,168
166 IF(XK - DABS(B(N)/H(N))) 70,7C,64
17C IF(CABS(B(N))) 70,7C,64
64 B(NN) = H(NN) - B(N-1)*Q
C B(N+1) TEST
C NEWTON*RAPHSON ITERATION
7C D(1) = H(1)
E(1) = D(1)
DO 72 J = 2, NN
C(J) = H(J) + D(J-1)*R
72 E(J) = D(J) + E(J-1)*R
IF(XK - DABS(D(NN)/H(NN))) 74,74,100
74 C(N) = -C(N-1)*P - C(N-2)*Q
SS = C(N-1)*C(N-1) - C(N)*C(N-2)
IF(SS) 76,78,76
76 P = P + (B(N)*C(N-1)-B(NNN)*C(N-2))/SS
Q = Q + (-B(N)*C(N) + B(NNN)*C(N-1))/SS
GO TO 70
78 P = P - 2.*
R = Q*(Q + 1.1)
GO TO 66
64 R = R - D(NN)/E(N)
66 II = II + 1
IF(II - L) 60,50,50
9C PS = PT
QS = Q1
PT = P
QT = Q
5Z XK = 1C*IXK
GO TO 26
C LINEAR EQUATION
10C IF(LT) 102,104,1C4
102 R = 1./R
104 U(N) = R
VIN = 0.*
CONVIN = XK
N = N-1
NN = N + 1
IF(N) 50C,500,1C6
1C6 DO 108 J = 1, NN
1C8 H(J) = D(J)
GO TO 10
C QUADRATIC EQUATION
15S P = H(NN)/H(NN-1)
20C IF(LT) 202,2C4,2C4
2C2 P = P/A
Q = 1./Q
204 SSS = P*Q/4.* - Q
SSSS = DSQR(DABS(SSS))
IF(SSSS) 26C,2C6,2C8
206 U(N) = -P/2.
U(N-1) = U(N)
VIN = SSSS
V(N-1) = -SSSS
GO TO 216
2C6 IF(P) 210,212,212
21C U(N) = -P/2. + SSSS
GO TO 214
212 U(N) = -P/2. - SSSS
214 U(N-1) = O/U(N)
VIN = C.*
V(N-1) = C.*
216 CONVIN = XK
CONVIN-1 = XK
N = N-2
NN = N + 1
IF(N) 50C,500,218
218 DO 22C J = 1,NN
CONVECTIVE HEAT-TRANSFER COEFFICIENTS FROM HARMONIC TEMPERATURE OSCILLATIONS - PHASE LAG ANGLE GIVEN

RUN 1

INPUT
K  RHO  CC  L  XL  TG  TGW  TC  WRADA  PHIRA
0.0007  0.2200  0.1170  0.0600  0.1667  960.0  658.0  970.0  1.2380  0.7673

OUTPUT
TCW  TEST1  TEST2  TEST  HCT  MGT  ERRER  R  PSIC  PSIG  GR
624.6  0.1152  0.9949  0.002121  0.000381  0.0051  5.5903  0.9764  5.4305  -0.0000

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 13, 1970,
129-04.
## APPENDIX - SYMBOLS

<table>
<thead>
<tr>
<th>Machine Engineering code</th>
<th>Engineering symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA</td>
<td>( \alpha )</td>
<td>thermal diffusivity, ( K/\rho C ), ( \text{in.}^2/\text{sec} ); ( \text{m}^2/\text{sec} )</td>
</tr>
<tr>
<td>CC</td>
<td>( c )</td>
<td>specific heat of wall material, ( \text{Btu/(lbm)(}^0\text{R)} ); ( J/(\text{kg})(^0\text{K}) )</td>
</tr>
<tr>
<td>ERROR</td>
<td>(--)</td>
<td>( 1.0 - (\text{TEST1})/(\text{TEST2}) )</td>
</tr>
<tr>
<td>ETA</td>
<td>( \eta )</td>
<td>frequency and wall property parameter, ( 1/\text{in.}; ( 1/\text{m} )</td>
</tr>
<tr>
<td>GR</td>
<td>(--)</td>
<td>cubic equation check of roots, equals zero for correct solution</td>
</tr>
<tr>
<td>HCA(1)</td>
<td>(--)</td>
<td>lower limits of the coolant-side convective heat-transfer coefficient</td>
</tr>
<tr>
<td>HCA(3)</td>
<td>(--)</td>
<td>upper limits of the coolant-side convective heat-transfer coefficient</td>
</tr>
<tr>
<td>HCT</td>
<td>( h_c )</td>
<td>time averaged convective heat-transfer coefficient on the coolant side of the wall, ( \text{Btu/(in.}^2)(\text{sec})(^0\text{R)} ); ( W/(\text{m}^2)(^0\text{K}) )</td>
</tr>
<tr>
<td>HGT</td>
<td>( h_G )</td>
<td>time averaged convective heat-transfer coefficient on hot-gas side of wall, ( \text{Btu/(in.}^2)(\text{sec})(^0\text{R)} ); ( W/(\text{m}^2)(^0\text{K}) )</td>
</tr>
<tr>
<td>LJK</td>
<td>(--)</td>
<td>number of iterations</td>
</tr>
<tr>
<td>IRDG</td>
<td>(--)</td>
<td>reading number</td>
</tr>
<tr>
<td>ISTA</td>
<td>(--)</td>
<td>station number</td>
</tr>
<tr>
<td>K</td>
<td>( K )</td>
<td>thermal conductivity of wall material, ( \text{Btu/}(\text{in.})(\text{sec})(^0\text{R)} ); ( J/(\text{m})(\text{sec})(^0\text{K}) )</td>
</tr>
<tr>
<td>L</td>
<td>( L )</td>
<td>thickness of wall material, ( \text{in.}; ( \text{m} )</td>
</tr>
<tr>
<td>NR</td>
<td>(--)</td>
<td>number of readings to be computed</td>
</tr>
<tr>
<td>OMDTG</td>
<td>( \theta/\Delta T_G )</td>
<td>ratio of amplitude of wall temperature to amplitude of sinusoidally driving hot-gas temperature</td>
</tr>
<tr>
<td>PHIRA</td>
<td>( \phi )</td>
<td>phase-lag angle between driving gas temperature and responding wall temperature, ( \text{rad} )</td>
</tr>
<tr>
<td>R</td>
<td>( R )</td>
<td>ratio of convective heat-transfer coefficients, ( h_c/h_G )</td>
</tr>
<tr>
<td>REAL1</td>
<td>( \psi_G )</td>
<td>convective heat-transfer parameter on hot-gas side of wall (JCL program), ( K\eta/h_G )</td>
</tr>
</tbody>
</table>
# Machine Engineering Code Symbols

<table>
<thead>
<tr>
<th>Code</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REAL2</td>
<td>$\psi_c$</td>
<td>convective heat-transfer parameter on coolant side of the wall, $K_\eta/h_c$</td>
</tr>
<tr>
<td>RHO</td>
<td>$\rho$</td>
<td>density of wall material, $\text{lbm/ft}^3; \text{g/m}^3$</td>
</tr>
<tr>
<td>XL</td>
<td>$x/L$</td>
<td>ratio of distance measured from the hot-gas side of wall to wall temperature measuring location to the wall thickness</td>
</tr>
<tr>
<td>TC</td>
<td>$\overline{T}_c$</td>
<td>mean temperature of the coolant, $^\circ R; K$</td>
</tr>
<tr>
<td>TCW</td>
<td>$T_{cw}$</td>
<td>calculated coolant wall temperature (JCL program), $^\circ R; K$</td>
</tr>
<tr>
<td>TCWA</td>
<td>$T_{cw}$</td>
<td>calculated coolant wall temperature (BL program), $^\circ R; K$</td>
</tr>
<tr>
<td>TEST1</td>
<td>$q_c$</td>
<td>heat flux to coolant, $\text{Btu/(in.}^2\text{)(sec)}; \text{W/m}^2$</td>
</tr>
<tr>
<td>TEST2</td>
<td>$q_G$</td>
<td>heat flux from hot gas, $\text{Btu/(in.}^2\text{)(sec)}; \text{W/m}^2$</td>
</tr>
<tr>
<td>TG</td>
<td>$\overline{T}_G$</td>
<td>mean temperature of hot gas, $^\circ R; K$</td>
</tr>
<tr>
<td>TGW</td>
<td>$T(x, \tau)$</td>
<td>wall temperature, function of distance (measured into wall from hot surface) and time (JCL program), $^\circ R; K$</td>
</tr>
<tr>
<td>TWL</td>
<td>$T(L, \tau)$</td>
<td>wall temperature, function of time at $x = L$ (BL program), $^\circ R; K$</td>
</tr>
<tr>
<td>TWO</td>
<td>$T(O, \tau)$</td>
<td>wall temperature, function of time at $x = 0$ (BL program), $^\circ R; K$</td>
</tr>
<tr>
<td>WRAD</td>
<td>$f$</td>
<td>frequency of temperature oscillations (BL program), rad/sec</td>
</tr>
<tr>
<td>WRADA</td>
<td>$f$</td>
<td>frequency of temperature oscillations (JCL program), rad/sec</td>
</tr>
</tbody>
</table>
REFERENCES

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546