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LOS ALAMOS SCIENTIFIC LABORATORY
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**MULTIREGION ANALYSIS OF TEMPERATURE FIELDS
AND HEAT FLUXES IN TUBE BUNDLES WITH
INTERNAL, SOLID, NUCLEAR HEAT SOURCES**

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**MULTIREGION ANALYSIS OF TEMPERATURE FIELDS
AND HEAT FLUXES IN TUBE BUNDLES WITH
INTERNAL, SOLID, NUCLEAR HEAT SOURCES**

by

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ABSTRACT

A two-dimensional, coupled, multiregion analysis of the fully developed temperature and velocity fields in triangular tube bundles with internal, solid nuclear heat sources is presented. Analytical and numerical results for the circumferential variations in the inside and outside tube wall surface temperatures, the tube wall temperature drop, and the inside and outside tube wall heat fluxes are given. The sensitivity of these variations to the pitch-to-diameter ratio of the tube bundle for both the slug flow and the laminar flow coolant cases is investigated.

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1. INTRODUCTION

The topic of this report is a multiregion analysis of the fully developed temperature and velocity fields which occur in tube bundles with solid internal nuclear heat sources. A sequel report¹ contains a multiregion thermal analysis of the temperature and velocity fields in tube bundles with internal nuclear heat sources consisting of molten nuclear reactor fuels in free convection and cooled by fluids in forced convection.

The tube bundles considered herein are triangular with the tube centers located at the vertices of equilateral triangles. Previous related work, which does not apply to tube bundles with internal nuclear heat sources, for reasons given below, is that of Sparrow, Loeffler, and Hubbard.² Under the restrictive assumption of a uniform outside wall temperature, Sparrow et al. have presented an analysis of fully developed heat transfer to a coolant in forced, convective, longitudinal laminar flow in triangular tube bundles. It is just this assumption of a uniform outside wall temperature which renders their analysis inapplicable to tube bundles with internal nuclear heat sources in which neither the outside nor the inside tube wall temperature is, in fact, uniform.

The circumferential variations of the inside and outside tube wall temperatures in tube bundles with internal nuclear heat sources become severe as the pitch-to-diameter ratio of the tube bundle is decreased and as the power density in the nuclear fuel region is increased.

To predict quantitatively the magnitude of the circumferential variations of the inside and outside tube wall temperatures and heat fluxes and the circumferential variation of the tube wall temperature drop, the appropriate energy and momentum balances for the temperature and velocity fields in all regions of the tube bundle must be set up and solved simultaneously. In the work of Sparrow, Loeffler, and Hubbard² only the single region energy balance for the coolant temperature and the momentum balance for the laminar flow coolant velocity field were considered along with the unrealistic boundary condition of a uniform outside wall temperature. In this report the coupled, multiregion problem for tube bundles with internal nuclear heat sources is considered.

We now turn to the formulation of the coupled, multiregion problem.

2. MATHEMATICAL FORMULATION

Owing to the symmetries existing in an infinite tube bundle with tube centers located on the vertices of equilateral triangles, only the composite domain shown in Fig. 1 need be considered. This domain consists of the nuclear fuel region for $0 < r < a$ and $0 < \phi < 30^\circ$, the tube wall region for $a < r < b$ and $0 < \phi < 30^\circ$, and the coolant region for $b < r < c/\cos \phi$ and $0 < \phi < 30^\circ$.

Fig. 1 Basic Composite Domain for an Infinite Triangular Tube Bundle

Under the assumptions of thermally isotropic materials and constant physical properties, the temperature fields in the fuel region and the tube wall region, respectively, satisfy Poisson's equation,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial v}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v}{\partial \phi^2} + \frac{q}{k} = 0, \quad (1)$$

and Laplace's equation,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial t}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 t}{\partial \phi^2} = 0. \quad (2)$$

The volumetric heat source term, q , in equation (1) is, in general, a function of both the radial and the azimuthal coordinates. For thermal reactor fuel element clusters, the spatial dependence of the volumetric heat source term may, in principle, be obtained from two-dimensional fine structure calculations. In fast reactor fuel element clusters, the power density spatial variation within a tube is, in fact, quite flat. Equation (1) will be solved for an arbitrary volumetric heat source term, and then the results will be specialized to a constant power density as, in practice, the precise spatial variation of the power density is seldom known.

If the coolant is in fully developed laminar flow, its velocity field satisfies

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u}{\partial \phi^2} = \frac{1}{\mu} \frac{\partial p}{\partial z}. \quad (3)$$

When the viscous dissipation terms are neglected, the energy balance for the coolant temperature field becomes

$$\rho c_p u \frac{\partial T}{\partial z} = k_c \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (4)$$

For a fully developed thermal boundary layer, the axial temperature gradient is constant, viz.,

$$w c_p \frac{\partial T}{\partial z} = w c_p \frac{\partial T_m}{\partial z} = \pi a^2 q, \quad (5)$$

and equation (4) specializes to

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} = \frac{\pi a^2 q \rho u}{w k_c} \quad (6)$$

The preceding field equations will be solved for two cases of coolant flow. In the first case the coolant will be in slug flow, and in the second, laminar flow. Even though slug flow does not exist in nature, the slug flow approximation is useful in estimating energy transport by molecular conduction in liquid metal coolants in turbulent flow. The circumferential variations of the inside and outside tube wall temperatures are more severe when the coolant is in laminar flow. Accordingly, the laminar flow coolant case is of interest in that it provides an upper limit for the circumferential variations of the tube wall temperatures. A quantitative estimate of how much less severe the tube wall temperature variations are in the turbulent flow coolant case than for a laminar flow coolant is provided through the slug flow coolant approximation. This estimate is restricted to coolants with low Prandtl numbers, i.e., liquid metals.

In the slug flow case, equations (1), (2), and (6) with $u = \text{constant}$ will be integrated simultaneously, while for laminar flow, solutions of equations (1)-(3) and (6) will be obtained simultaneously. In both types of coolant flow, these coupled boundary value problems are subject to the boundary conditions which follow.

$$\frac{\partial v}{\partial \phi}(r, 0) = \frac{\partial v}{\partial \phi}(r, \pi/6) = 0, \quad (7)$$

$$\frac{\partial t}{\partial \phi}(r, 0) = \frac{\partial t}{\partial \phi}(r, \pi/6) = 0, \quad (8)$$

$$\frac{\partial T}{\partial \phi}(r, 0) = \frac{\partial T}{\partial \phi}(r, \pi/6) = 0, \quad (9)$$

$$\frac{\partial u}{\partial \phi}(r, 0) = \frac{\partial u}{\partial \phi}(r, \pi/6) = 0. \quad (10)$$

$$v(a, \phi) = t(a, \phi), \quad (11)$$

$$k \frac{\partial v}{\partial r}(a, \phi) = k_w \frac{\partial t}{\partial r}(a, \phi), \quad (12)$$

$$t(b, \phi) = T(b, \phi), \quad (13)$$

$$k_w \frac{\partial t}{\partial r}(b, \phi) = k_c \frac{\partial T}{\partial r}(b, \phi), \quad (14)$$

$$u(b, \phi) = 0, \quad (15)$$

$$\vec{n} \cdot \text{grad } u \Big|_{r=c/\cos \phi} = \cos \phi \frac{\partial u}{\partial r}(c/\cos \phi, \phi) - \sin \phi (\cos \phi / c) \cdot \frac{\partial u}{\partial \phi}(c/\cos \phi, \phi) = 0, \quad (16)$$

and

$$\begin{aligned} \vec{n} \cdot \text{grad } T \Big|_{r=c/\cos \phi} &= \cos \phi \frac{\partial T}{\partial r} (c/\cos \phi, \phi) - \\ &- \sin \phi (\cos \phi / c) \frac{\partial T}{\partial \phi} (c/\cos \phi, \phi) = 0. \end{aligned} \quad (17)$$

Boundary conditions of the type given in equations (16) and (17) along the line $r = c/\cos \phi$ in the composite domain shown in Fig. 1 are derived in Appendix A. In practice these boundary conditions are satisfied only at a finite number of points as will be seen later. In addition to the above boundary conditions, the temperature field of the fuel region must remain finite at the origin.

3. GENERAL SOLUTIONS OF THE FIELD EQUATIONS

3.1. Fuel Region Temperature Field

General solutions of equations (1)-(3) and (6) which satisfy the homogeneous Neumann boundary conditions expressed in equations (7)-(10) will now be obtained. The remaining boundary conditions will be satisfied subsequently in Section 4.

Upon taking the finite Fourier cosine transform³ with respect to the azimuthal coordinate of equation (1), we find that

$$\frac{1}{r} \frac{d}{dr} \left[r \frac{dv_c}{dr} (r, n) \right] - \frac{36n^2}{r^2} v_c(r, n) + \frac{1}{k} q_c(r, n) = 0 \quad (18)$$

in which the finite Fourier cosine transforms of the fuel region temperature field and the power density are, by definition, given by

$$\begin{Bmatrix} v_c(r, n) \\ q_c(r, n) \end{Bmatrix} = \int_0^{\pi/6} d\phi \cos(6n\phi) \begin{Bmatrix} v(r, \phi) \\ q(r, \phi) \end{Bmatrix} \quad (n = 0, 1, 2, 3, \dots),$$

respectively. For $n = 0$, the general solution of equation (18) is

$$v_c(r,0) = (\pi/6)A_0 + (\pi/6)B_0 \ln(r) + (1/k) \int_0^a dy y q_c(y,0) K_0(r,y) \quad (19)$$

where the Green's function, $K_0(r,y)$, is

$$K_0(r,y) = \begin{cases} \ln(a/y) & \text{if } r < y \\ \ln(a/r) & \text{if } r > y \end{cases} \quad (20)$$

The general solution of equation (18) for $n = 1, 2, 3, \dots$ is found to be

$$v_c(r,n) = (\pi/12)A_n r^{-6n} + (\pi/12)B_n r^{6n} + (1/k) \int_0^a dy y q_c(y,n) K_{6n}(r,y). \quad (21)$$

The Green's function, $K_{6n}(r,y)$, in equation (21) is given by

$$K_{6n}(r,y) = \begin{cases} (1/12n)(r/a)^{6n} \left[(a/y)^{6n} - (y/a)^{6n} \right] & \text{if } r < y \\ (1/12n)(y/a)^{6n} \left[(a/r)^{6n} - (r/a)^{6n} \right] & \text{if } r > y \end{cases} \quad (22)$$

The Green's functions appearing in equations (20) and (22) are derived in Appendix B.

Upon application of the inversion theorem for the finite Fourier cosine transform³ together with equations (19) and (21) with $B_0 = 0$ and $A_n = 0$ (temperature is finite at the origin), the general solution of equation (1) for the fuel region temperature field is obtained, viz.,

$$\begin{aligned}
v(r, \phi) = A_0 + \sum_{n=1}^{\infty} B_n r^{6n} \cos(6n\phi) + (6/\pi k) \int_0^a dy y q_c(y, 0) K_0(r, y) + \\
+ (12/\pi k) \sum_{n=1}^{\infty} \cos(6n\phi) \int_0^a dy y q_c(y, n) K_{6n}(r, y). \quad (23)
\end{aligned}$$

This result, which satisfies the boundary conditions of equation (7), holds for an arbitrary spatial variation, $q(r, \phi)$, of the fuel region power density. Under the assumption of a uniform power density with a finite Fourier cosine transform,

$$q_c(r, n) = \begin{cases} (\pi/6)q & \text{if } n = 0 \\ 0 & \text{if } n = 1, 2, 3, \dots \end{cases}, \quad (24)$$

the fuel region temperature field found in equation (23) specializes down to

$$v(r, \phi) = A_0 + (qa^2/4k) [1 - (r/a)^2] + \sum_{n=1}^{\infty} B_n r^{6n} \cos(6n\phi). \quad (25)$$

This result for the fuel temperature field will be used in the subsequent analysis, and the arbitrary constants, B_n , will be calculated in Section 4.1 for the slug flow coolant and in Section 4.2 for the laminar flow coolant.

3.2 Tube Wall Temperature Field

The finite Fourier cosine transform, $t_c(r, n)$, of the tube wall temperature satisfies the ordinary differential equation,

$$\frac{1}{r} \frac{d}{dr} \left[r \frac{dt_c}{dr} (r, n) \right] - \frac{36n^2}{r^2} t_c(r, n) = 0 \quad (26)$$

obtained from equation (2). For $n = 0$ the general solution of equation (26) is

$$t_c(r, 0) = \pi c_0/6 + (\pi d_0/6) \ln(r), \quad (27)$$

while for $n = 1, 2, 3, \dots$ the general solution of equation (26) is

$$t_c(r, n) = (\pi c_n/12) r^{6n} + (\pi d_n/12) r^{-6n}. \quad (28)$$

Application of the inversion theorem for the finite Fourier cosine transform now yields

$$t(r, \phi) = c_0 + d_0 \ln(r) + \sum_{n=1}^{\infty} \left(c_n r^{6n} + d_n r^{-6n} \right) \cos(6n\phi) \quad (29)$$

as the general solution for the tube wall temperature field which satisfies the boundary conditions of equation (8). The arbitrary constants, c_0 , d_0 , c_n , and d_n appearing in equation (29) will be computed in Section 4.1 for a coolant in slug flow and Section 4.2 for a coolant in laminar flow.

3.3 Velocity Field for the Coolant in Laminar Flow

Let $u_c(r, n)$ be the finite Fourier cosine transform of the coolant velocity field in the case of laminar flow. Then, from equation (3) it follows that

$$\frac{1}{r} \frac{d}{dr} \left[r \frac{du_c}{dr} (r, n) \right] - \frac{36n^2}{r^2} u_c(r, n) = \frac{1}{\mu} \frac{\partial p}{\partial z} \frac{\pi}{6} \delta_{n0} \quad (30)$$

wherein δ_{n0} is the Kronecker delta. For $n = 0$ the general solution of equation (30) is

$$u_c(r, 0) = (\pi r^2 / 24\mu) \frac{\partial p}{\partial z} + (\pi/6) C_0^L \ln(r) + (\pi/6) D_0^L, \quad (31)$$

and for $n = 1, 2, 3, \dots$ we obtain

$$u_c(r, n) = (\pi/12) C_n^L r^{6n} + (\pi/12) D_n^L r^{-6n}. \quad (32)$$

Hence, the inversion theorem yields

$$u(r, \phi) = D_0^L + C_0^L \ln(r) + (r^2/4\mu) \frac{\partial p}{\partial z} + \sum_{n=1}^{\infty} \left(C_n^L r^{6n} + D_n^L r^{-6n} \right) \cos(6n\phi) \quad (33)$$

as the general solution of equation (3) which satisfies the boundary conditions of equation (10). The nonslip condition at the tube wall expressed in equation (15) requires that

$$D_n^L = -C_n^L b^{12n} \quad (34)$$

and

$$D_0^L = -C_0^L \ln(b) - (b^2/4\mu) \frac{\partial p}{\partial z} \quad (35)$$

so that equation (33) reduces to

$$u(r, \phi) = C_0^L \ln(r/b) + \left[(b^2 - r^2)/4\mu \right] \left(-\frac{\partial p}{\partial z} \right) + \sum_{n=1}^{\infty} C_n^L b^{6n} \left[(r/b)^{6n} - (b/r)^{6n} \right] \cos(6n\phi). \quad (36)$$

The constant C_0^L in equation (36) is to be determined by the requirement that the total drag force exerted on the coolant by the tube wall must equal the net pressure force acting over the coolant cross section, i.e.,

$$\int_0^{\pi/6} \mu \frac{\partial u}{\partial r} (b, \phi) b d\phi = \int_0^{\pi/6} d\phi \int_b^{c/\cos\phi} \left(-\frac{\partial p}{\partial z} \right) r dr. \quad (37)$$

Upon substituting equation (36) into equation (37) and carrying through the indicated integrations, it is found that

$$C_0^L = (\sqrt{3} c^2/\pi) \left(-\frac{1}{\mu} \frac{\partial p}{\partial z} \right). \quad (38)$$

The last boundary condition to be satisfied by the laminar flow velocity field obtained in equation (36) is that of equation (16). With equation (36) it follows that equation (16) becomes

$$\sum_{n=1}^{\infty} \left\{ \cos^{1-6n}(\phi) \cos[(6n-1)\phi] + (b/c)^{12n} \cos^{6n+1}(\phi) \cos[(6n+1)\phi] \right\} \Delta_n = \frac{1}{2} - \frac{\sqrt{3}}{\pi} \cos^2(\phi) \quad (39)$$

in which the definition,

$$\Delta_n = \left(6nC_n^L c^{6n-2}/\mu \right) \left(- \frac{\partial p}{\partial z} \right), \quad (40)$$

has been introduced.

Equation (39) can not and need not be satisfied at all points on the line $r = c/\cos \phi$ to obtain an accurate result for the laminar flow velocity field. Let N be the number of points on the line $r = c/\cos \phi$ at which equation (39) is satisfied. If these points are arbitrarily equally spaced, then equation (39) will be satisfied at the angular positions ϕ_j such that

$$\phi_j = \frac{(j-1)\pi}{(N-1)6} \quad \text{for } j = 1, 2, 3, \dots, N, \quad (41)$$

and equation (39) accordingly reduces down to a set of linear, inhomogeneous algebraic equations for the Δ_n 's, viz.,

$$\sum_{n=1}^N D_{jn} \Delta_n = \frac{1}{2} - \frac{\sqrt{3}}{\pi} \cos^2 \left[\frac{(j-1)\pi}{(N-1)6} \right] \quad (j = 1, 2, \dots, N) \quad (42)$$

with matrix elements

$$D_{jn} = \cos^{1-6n} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[(6n-1) \frac{(j-1)\pi}{(N-1)6} \right] + \\ + (b/c)^{12n} \cos^{6n+1} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[(6n+1) \frac{(j-1)\pi}{(N-1)6} \right]. \quad (43)$$

It will be noted that the Δ_n 's are functions only of the pitch-to-diameter ratio of the tube bundle, i.e., they are geometric parameters. Once the set, equation (42), has been solved for a specified value of

N, the laminar flow velocity field is to be determined from

$$u(r, \phi) = c^2 \left(-\frac{1}{\mu} \frac{\partial p}{\partial z} \right) \left((\sqrt{3}/\pi) \ln(r/b) - (1/4) \left[(r/c)^2 - (b/c)^2 \right] + \sum_{n=1}^N (\Delta_n/6n) \left\{ \left[(r/c)^{6n} - (b/c)^{6n} (b/r)^{6n} \right] \cos(6n\phi) \right\} \right). \quad (44)$$

The volumetric flow rate of the coolant may be calculated from equation (44). If Q is the coolant volumetric flow rate through the coolant cross section of the composite domain shown in Fig. 1 and w is the entire coolant mass flow rate for a single tube in the tube bundle, then

$$Q = w/(12\rho) = \int_0^{\pi/6} d\phi \int_b^{c/\cos\phi} r dr u(r, \phi). \quad (45)$$

Equations (44) and (45) yield

$$Q = c^4 \left(-\frac{1}{\mu} \frac{\partial p}{\partial z} \right) M = w/(12\rho) \quad (46)$$

wherein

$$M = \frac{1}{2\pi} \left[-\frac{3}{2} + \ln\left(\frac{c}{b}\right) - \ln\left(\frac{\sqrt{3}}{2}\right) \right] + \frac{13\sqrt{3}}{216} + \frac{\sqrt{3}}{12} \left(\frac{b}{c}\right)^2 - \frac{\pi}{96} \left(\frac{b}{c}\right)^4 + \sum_{n=1}^N \frac{\Delta_n}{6n} \left[\frac{r_n}{6n+2} + \left(\frac{b}{c}\right)^{12n} \frac{\lambda_n}{6n-2} \right]. \quad (47)$$

In equation (47) these definitions have been introduced:

$$\Gamma_n = \int_0^{\pi/6} \cos^{-2-6n}(\phi) \cos(6n\phi) d\phi \quad (48)$$

and

$$\lambda_n = \int_0^{\pi/6} \cos^{6n-2}(\phi) \cos(6n\phi) d\phi. \quad (49)$$

The discrete variable functions, Γ_n and λ_n , may be computed with Simpson's rule, viz.,

$$\begin{aligned} \Gamma_n = \frac{\pi}{18(K-1)} & \left\{ 1 + 4 \sum_{j=1}^{j=(K-1)/2} \cos^{-2-6n} \left[\frac{(2j-1)\pi}{(K-1)6} \right] \cos \left[\frac{n\pi(2j-1)}{(K-1)} \right] + \right. \\ & \left. + 2 \sum_{j=1}^{j=(K-3)/2} \cos^{-2-6n} \left[\frac{j\pi}{3(K-1)} \right] \cos \left[\frac{2jn\pi}{(K-1)} \right] + \cos(n\pi) \cos^{-2-6n}(\pi/6) \right\} \quad (50) \end{aligned}$$

and

$$\begin{aligned} \lambda_n = \frac{\pi}{18(K-1)} & \left\{ 1 + 4 \sum_{j=1}^{j=(K-1)/2} \cos \left[\frac{n\pi(2j-1)}{(K-1)} \right] \cos^{6n-2} \left[\frac{(2j-1)\pi}{(K-1)6} \right] + \right. \\ & \left. + 2 \sum_{j=1}^{j=(K-3)/2} \cos \left[\frac{2jn\pi}{(K-1)} \right] \cos^{6n-2} \left[\frac{j\pi}{3(K-1)} \right] + \cos(n\pi) \cos^{6n-2}(\pi/6) \right\}. \quad (51) \end{aligned}$$

In equations (50) and (51) the number of points, K , at which the integrands of equations (48) and (49) are evaluated must be odd and such that $K \geq 5$. Values of Γ_n and λ_n computed from equations (50) and (51) with $K = 251$ are shown in Table 1 for $n = 1, 2, 3, \dots, 20$.

Equations (42), (44), and (47) have been previously reported by Sparrow and Loeffler⁴ who obtained them by a different method from that used in this report. Equation (44) has been derived in detail here to demonstrate that all the field equations arising in the multiregion thermal analysis of tube bundles with internal nuclear heat sources can be solved from a consistent, unified point of view when the method of finite Fourier cosine transforms is used on the ϕ -coordinate. Values of the parameter, M , as computed from equation (47) are presented in Table 2. This table, which extends the number of values of the pitch-to-diameter ratio $P/D = c/b$, of the tube bundle considered by Sparrow and Loeffler,⁴ exhibits the values found for the parameter, M , as a function of N , the number of points at which the boundary condition of equation (16) is satisfied, for each value of the pitch-to-diameter ratio. It will be noted from Table 2 that for very tight tube bundles we must take at least $N = 4$ to obtain three significant figures for M and that for loose tube bundles $N = 2$ is sufficient for three significant figures in M . Over the entire range of pitch-to-diameter ratios, $N = 6$ is sufficient to get five significant figures in the value of the parameter, M , which is related to the volumetric or mass flow rate through equation (46).

In Tables 3, 4, and 5 values of the coefficients, Δ_n , which are solutions of the set, equation (42), are tabulated. In Table 3 the variations in the Δ_n values obtained as the number of points, N , at which the boundary condition of equation (16) is increased are shown as N ranges from 2 to 15 for a pitch-to-diameter ratio of $P/D = 1.01$. The same variations are shown in Table 4 for $P/D = 1.25$. In Table 5 values of the coefficients, Δ_n , are tabulated as functions of the pitch-to-diameter ratio, P/D , of the tube bundle. All of the values in Table 5

were calculated by solving the set, equation (42), for $N = 15$ so that the boundary condition of equation (16) is satisfied at 15 points.

TABLE 1

Values of Γ_n and λ_n versus n

<u>n</u>	<u>Γ_n</u>	<u>λ_n</u>
1	-0.19551	0.048714
2	0.24953	-0.0093415
3	-0.40470	0.0025500
4	0.72906	-0.0007952
5	-1.39367	0.0002661
6	2.76780	-0.0000930
7	-5.64526	0.0000335
8	11.7428	-0.0000123
9	-24.7983	0.0000046
10	52.999	-0.0000018
11	-114.38	0.0000007
12	248.83	-0.0000003
13	-545.03	0.0000001
14	1200.7	-0.0000004
15	-2658.	0.0000002
16	5912.	0
17	-1.320(4)*	0
18	2.956(4)	0
19	-6.641(4)	0
20	1.496(5)	0

*The number in parentheses is the power of ten that gives the order of magnitude, e.g., $-1.320(3) = -1.320 \times 10^3$.

TABLE 2

Values of the Parameter, M , versus the Pitch-to-Diameter Ratio, $P/D = c/b$, of the Tube Bundle and the Number of Points, N , at Which Equation (16) is Satisfied

<u>P/D</u>	<u>N = 2</u>	<u>N = 3</u>	<u>N = 4</u>	<u>N = 5</u>	<u>N = 6</u>
1.01	0.11262(-3)*	0.11458(-3)	0.11320(-3)	0.11333(-3)	0.11334(-3)
1.02	.14388(-3)	.14623(-3)	.14506(-3)	.14518(-3)	.14517(-3)
1.03	.18130(-3)	.18393(-3)	.18300(-3)	.18310(-3)	.18310(-3)
1.04	.22544(-3)	.22826(-3)	.22756(-3)	.22764(-3)	.22763(-3)
1.05	.27677(-3)	.27969(-3)	.27920(-3)	.27925(-3)	.27925(-3)
1.10	.65241(-3)	.65510(-3)	.65518(-3)	.65518(-3)	.65518(-3)
1.15	.12429(-2)	.12448(-2)	.12450(-2)	.12450(-2)	.12450(-2)
1.20	.20542(-2)	.20555(-2)	.20557(-2)	.20557(-2)	.20557(-2)
1.25	.30796(-2)	.30804(-2)	.30805(-2)	.30805(-2)	.30805(-2)
1.30	.43045(-2)	.43049(-2)	.43050(-2)	.43050(-2)	.43050(-2)
1.50	.10825(-1)	.10825(-1)	.10825(-1)	.10825(-1)	.10825(-1)
2.00	.32966(-1)	.32966(-1)	.32966(-1)	.32966(-1)	.32966(-1)
4.00	.11814	.11814	.11814	.11814	.11814

*The number in parentheses indicates the power of ten that gives the order of magnitude (see Table 1).

TABLE 3

Values of the Coefficients, Δ_n , versus the Number of Points, N , where Equation (16) is Satisfied for a Pitch-to-Diameter Ratio, $P/D = 1.01$.

	$N = 2$	$N = 3$	$N = 4$	$N = 5$	$N = 6$	$N = 7$	$N = 15$
Δ_1	-0.31806(-1)	-0.32553(-1)	-0.31876(-1)	-0.31901(-1)	-0.31900(-1)	-0.31900(-1)	-0.31900(-1)
Δ_2	0.48687(-2)	0.53249(-2)	0.51588(-2)	0.52445(-2)	0.52366(-2)	0.52369(-2)	0.52369(-2)
Δ_3	-----	0.34979(-3)	-0.12187(-3)	-0.11605(-3)	-0.12920(-3)	-0.12958(-3)	-0.12949(-3)
Δ_4	-----	-----	-0.11058(-3)	-0.16626(-3)	-0.15733(-3)	-0.16563(-3)	-0.16512(-3)
Δ_5	-----	-----	-----	-0.17047(-4)	-0.56106(-5)	-0.37963(-5)	-0.51029(-5)
Δ_6	-----	-----	-----	-----	0.25043(-5)	0.83303(-5)	0.83889(-5)
Δ_7	-----	-----	-----	-----	-----	0.15267(-5)	0.23788(-5)
Δ_8	-----	-----	-----	-----	-----	-----	0.79609(-7)
Δ_9	-----	-----	-----	-----	-----	-----	-0.18310(-6)
Δ_{10}	-----	-----	-----	-----	-----	-----	-0.84428(-7)
Δ_{11}	-----	-----	-----	-----	-----	-----	-0.19524(-7)
Δ_{12}	-----	-----	-----	-----	-----	-----	0.35014(-9)
Δ_{13}	-----	-----	-----	-----	-----	-----	0.31963(-8)
Δ_{14}	-----	-----	-----	-----	-----	-----	0.16046(-8)
Δ_{15}	-----	-----	-----	-----	-----	-----	0.28512(-9)

TABLE 4

Values of the Coefficients, Δ_n , versus the Number of Points, N , where Equation (16) is Satisfied for a Pitch-to-Diameter Ratio, $P/D = 1.25$.

	$N = 2$	$N = 3$	$N = 4$	$N = 5$	$N = 6$	$N = 7$	$N = 15$
Δ_1	-0.48040(-1)	-0.48230(-1)	-0.48260(-1)	-0.48259(-1)	-0.48259(-1)	-0.48259(-1)	-0.48259(-1)
Δ_2	0.12695(-4)	0.13073(-3)	0.13223(-3)	0.13019(-3)	0.13019(-3)	0.13020(-3)	0.13020(-3)
Δ_3	-----	0.83947(-4)	0.10692(-3)	0.10696(-3)	0.10689(-3)	0.10689(-3)	0.10690(-3)
Δ_4	-----	-----	0.71740(-5)	0.85530(-5)	0.85758(-5)	0.85675(-5)	0.85601(-5)
Δ_5	-----	-----	-----	0.41592(-6)	0.45644(-6)	0.44454(-6)	0.45337(-6)
Δ_6	-----	-----	-----	-----	0.71124(-8)	0.18685(-7)	0.20345(-7)
Δ_7	-----	-----	-----	-----	-----	0.62575(-8)	-0.98040(-9)
Δ_8	-----	-----	-----	-----	-----	-----	0.24700(-9)
Δ_9	-----	-----	-----	-----	-----	-----	0.44855(-9)
Δ_{10}	-----	-----	-----	-----	-----	-----	0.94824(-9)
Δ_{11}	-----	-----	-----	-----	-----	-----	0.88071(-9)
Δ_{12}	-----	-----	-----	-----	-----	-----	0.10912(-8)
Δ_{13}	-----	-----	-----	-----	-----	-----	0.97895(-9)
Δ_{14}	-----	-----	-----	-----	-----	-----	0.48969(-9)
Δ_{15}	-----	-----	-----	-----	-----	-----	0.10275(-9)

TABLE 5

Values of the Coefficients, Δ_n , versus the Pitch-to-Diameter Ratio of the Tube Bundle when Equation (16) is Satisfied at Fifteen Points ($N = 15$).

P/D	Δ_1	Δ_2	Δ_3	Δ_4	Δ_5	Δ_6
1.01	-0.31900(-1)	0.52369(-2)	-0.12949(-3)	-0.16512(-3)	-0.51029(-5)	0.83889(-5)
1.02	-0.33207(-1)	0.50801(-2)	0.23851(-4)	-0.14397(-3)	-0.15751(-4)	0.35222(-5)
1.03	-0.34463(-1)	0.48702(-2)	0.15057(-3)	-0.11469(-3)	-0.19260(-4)	0.26269(-6)
1.04	-0.35664(-1)	0.46183(-3)	0.24789(-3)	-0.84211(-4)	-0.18271(-4)	-0.12818(-5)
1.05	-0.36806(-1)	0.43359(-2)	0.31689(-3)	-0.56774(-4)	-0.15239(-4)	-0.17192(-5)
1.10	-0.41570(-1)	0.28029(-2)	0.37815(-3)	0.10827(-4)	-0.24136(-5)	-0.50802(-6)
1.15	-0.44835(-1)	0.15384(-2)	0.27359(-3)	0.17639(-4)	0.42221(-6)	-0.47939(-7)
1.20	-0.46940(-1)	0.77817(-3)	0.17485(-3)	0.13096(-4)	0.62307(-6)	0.18752(-7)
1.25	-0.48259(-1)	0.13020(-3)	0.10689(-3)	0.85601(-5)	0.45337(-6)	0.20345(-7)
1.30	-0.49079(-1)	-0.21198(-3)	0.63523(-4)	0.54303(-5)	0.29563(-6)	0.14711(-7)
1.50	-0.50245(-1)	-0.69915(-3)	0.13539(-5)	0.84254(-6)	0.48668(-7)	9.38301(-8)
2.00	-0.50499(-1)	-0.80537(-3)	-0.12194(-4)	-0.15570(-6)	-0.48999(-8)	0.14729(-8)
4.00	-0.50507(-1)	-0.80886(-3)	-0.12638(-4)	-0.18835(-6)	-0.66262(-8)	0.14439(-8)

*The number in parentheses indicates the power of ten that gives the order of magnitude (see Table 1).

3.4 Coolant Temperature Field for a Slug Flow Coolant

The general solution for the temperature field of the coolant in the slug flow case which satisfies the boundary conditions of equation (9) is obtained from equation (16) with $u = \text{constant}$. With

$$S = \pi a^2 q \rho u / w k_c \quad (52)$$

the finite Fourier cosine transform, $T_c(r, n)$, of the coolant temperature is, from equation (6), given by

$$\frac{1}{r} \frac{d}{dr} \left[r \frac{dT_c}{dr}(r, n) \right] - \frac{36n^2}{r^2} T_c(r, n) = (\pi S/6) \delta_{n0} . \quad (53)$$

For $n = 0$ the general solution of equation (53) is

$$T_c(r, 0) = \pi S r^2 / 24 + \pi E_0 / 6 + (\pi F_0 / 6) \ln(r), \quad (54)$$

while for $n = 1, 2, 3, \dots$ it is

$$T_c(r, n) = \pi E_n r^{6n} / 12 + \pi F_n r^{-6n} / 12 . \quad (55)$$

Hence, from the inversion theorem for the finite Fourier cosine transform, the solution of equation (6) with $u = \text{constant}$ satisfying equation (9) is found to be

$$T(r, \phi) = S r^2 / 4 + E_0 + F_0 \ln(r) + \sum_{n=1}^{\infty} \left(E_n r^{6n} + F_n r^{-6n} \right) \cos(6n\phi). \quad (56)$$

The arbitrary constants, E_0 , F_0 , E_n and F_n arising in equation (56) will subsequently be determined in Section 4.1 for slug flow.

3.5 Coolant Temperature Field for a Laminar Flow Coolant

In this section the general solution of equation (4) subject to the boundary conditions expressed in equation (9) will be computed for the case of a fully developed thermal boundary layer in the axial direction and of a coolant in laminar flow.

From equation (5), the condition for a fully developed thermal boundary layer in the axial direction, and from equation (46) the axial temperature gradient is

$$\frac{\partial T}{\partial z} = \pi a^2 q / \left[12 c_p \rho c^4 M \left(- \frac{1}{\mu} \frac{\partial p}{\partial z} \right) \right] \quad (57)$$

Upon substituting equations (44) and (57) into equation (4), the coolant temperature field in the laminar flow case is found to be given by

$$\begin{aligned} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} = \\ \frac{\pi a^2 q}{12 k_c c^2 M} \left\{ \frac{\sqrt{3}}{\pi} \ln \left(\frac{r}{b} \right) - \frac{1}{4} \left(\frac{r^2}{c^2} - \frac{b^2}{c^2} \right) + \sum_{n=1}^N \frac{\Delta_n}{6n} \left[\left(\frac{r}{c} \right)^{6n} - \left(\frac{b}{c} \right)^{6n} \left(\frac{b}{r} \right)^{6n} \right] \cos(6n\phi) \right\} \quad (58) \end{aligned}$$

Multiplying equation (58) through by $\cos(6n\phi)$ and integrating the result with respect to ϕ from 0 to $\pi/6$ yields an ordinary differential equation for the finite Fourier cosine transform, $T_c(r, m)$, of the coolant temperature field, viz.,

$$\begin{aligned} \frac{1}{r} \frac{d}{dr} \left[r \frac{dT_c}{dr} (r, m) \right] - \frac{36m^2}{r^2} T_c(r, m) = \frac{\pi a^2 q}{12k_c c^2 M} \left\{ \left[\frac{\sqrt{3}}{\pi} \ln \left(\frac{r}{b} \right) - \right. \right. \\ \left. \left. - \frac{1}{4} \left(\frac{r^2}{c^2} - \frac{b^2}{c^2} \right) \right] \frac{\pi}{6} \delta_{m0} + \sum_{n=1}^N \frac{\Delta_n}{6n} \left[\left(\frac{r}{c} \right)^{6n} - \left(\frac{b}{c} \right)^{6n} \left(\frac{b}{r} \right)^{6n} \right] \frac{\pi}{12} \delta_{mn} \right\}. \end{aligned} \quad (59)$$

For $m = 0$ the general solution of equation (59) is

$$\begin{aligned} T_c(r, 0) = (\pi/6) E_0^L + (\pi/6) F_0^L \ln(r) + \\ + \frac{\pi a^2 q}{12k_c c^2 M} \frac{\pi r^2}{6} \left[-\frac{\sqrt{3}}{4\pi} + \frac{\sqrt{3}}{4\pi} \ln \left(\frac{r}{b} \right) - \frac{r^2}{64c^2} + \frac{b^2}{16c^2} \right]. \end{aligned} \quad (60)$$

When $m = 1, 2, 3, \dots$ equation (59) is an inhomogeneous equidimensional equation which, after the transformation, $r = \exp(x)$, reduces to an ordinary differential equation with constant coefficients which, in turn, may be solved by the method of variation of parameters with the result that

$$\begin{aligned} T_c(r, m) = (\pi/12) E_m^L r^{6m} + (\pi/12) F_m^L r^{-6m} + \\ + \frac{\pi a^2 q}{12k_c c^2 M} \left(\frac{\pi}{12} \right) \frac{\Delta_m r^2}{24m} \left[\frac{(r/c)^{6m}}{6m+1} + \frac{(b/c)^{6m} (b/r)^{6m}}{6m-1} \right]. \end{aligned} \quad (61)$$

Accordingly, with the inversion theorem for the finite Fourier cosine transform, the general solution of equation ((58) for the coolant temperature field in the laminar flow case which satisfies the boundary conditions of equation (9) is obtained in the form which follows.

$$\begin{aligned}
 T(r, \phi) = & E_0^L + F_0^L \ln(r) + \sum_{n=1}^{\infty} \left(E_n^L r^{6n} + F_n^L r^{-6n} \right) \cos(6n\phi) + \\
 & + \frac{\pi a^2 q r^2}{12 k_c c^2 M} \left[-\frac{\sqrt{3}}{4\pi} + \frac{\sqrt{3}}{4\pi} \ln\left(\frac{r}{b}\right) - \frac{r^2}{64c^2} + \frac{b^2}{16c^2} \right] + \\
 & + \frac{\pi a^2 q r^2}{12 k_c c^2 M} \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(r/c)^{6n}}{6n+1} + \frac{(b/c)^{6n} (b/r)^{6n}}{6n-1} \right] \cos(6n\phi).
 \end{aligned} \tag{62}$$

The arbitrary constants, E_0^L , F_0^L , E_n^L , and F_n^L in equation (62) will be calculated in Section 4.2 for the case of a coolant in laminar flow.

4. LINEAR ALGEBRAIC EQUATIONS FOR THE ARBITRARY CONSTANTS APPEARING IN THE GENERAL SOLUTIONS OF THE TEMPERATURE FIELD EQUATIONS

In Section 3 general solutions for the nuclear fuel region temperature field, the tube wall temperature field, and the coolant temperature field have been obtained subject to the homogeneous Neumann boundary conditions on the lines $\phi = 0$ and $\phi = \pi/6$ as expressed in equations (7)-(9). In this section the problem of determining the temperature fields within the composite domain shown in Fig. 1 will be reduced to a problem in matrix inversion. This will be accomplished by first eliminating all the arbitrary constants in the general solutions for the temperature fields except the B_n 's of equation (25) by imposing the physical requirements of continuous temperatures and heat fluxes at both the inside and outside surfaces of the tube wall, i.e., by satisfying the boundary conditions of equations (11)-(14). Then, a set of inhomogeneous, linear

algebraic equations for a finite number, N , of the B_n 's arising in equation (25) will be obtained by requiring that the coolant temperature field satisfy the homogeneous Neumann boundary condition of equation (17) at a finite number, N , of points.

4.1 Coolant in Slug Flow

When equations (25) and (29) are substituted into equations (11) and (12) there follows

$$A_0 + \sum_{n=1}^{\infty} a^{6n} B_n \cos(6n\phi) = c_0 + d_0 \ln(a) + \sum_{n=1}^{\infty} \left(c_n a^{6n} + d_n a^{-6n} \right) \cos(6n\phi) \quad (63)$$

and

$$-qa/2 + \sum_{n=1}^{\infty} k_6 n a^{6n-1} B_n \cos(6n\phi) = d_0 k_w / a + \sum_{n=1}^{\infty} k_w 6n \left(c_n a^{6n-1} - d_n a^{-6n-1} \right) \cos(6n\phi) . \quad (64)$$

Integrating equations (63) and (64) through with respect to ϕ from $\phi = 0$ to $\phi = \pi/6$ and solving the resulting pair of algebraic equations for c_0 and d_0 yields

$$c_0 = A_0 + \left(qa^2 / 2k_w \right) \ln(a) \quad (65)$$

and

$$d_0 = -qa^2/2k_w \quad (66)$$

Operating on equations (63) and (64) with the integral operator $\int_0^{\pi/6} d\phi \cos(6m\phi)$ and solving the resulting algebraic equations for c_n and d_n produces

$$c_n = (1 + \kappa_w) (B_n/2) \quad (67)$$

and

$$d_n = a^{12n} (1 - \kappa_w) (B_n/2) \quad (68)$$

wherein the definition, $\kappa_w = k/k_w$ has been introduced.

Upon following the identical procedure on the outside surface of the tube wall with equations (29), (56), (13), and (14), it is found that

$$F_0 = -Sb^2/2 - qa^2/2k_c, \quad (69)$$

$$E_0 = A_0 - \frac{Sb^2}{4} - \frac{qa^2}{2k_w} \ln\left(\frac{b}{a}\right) + \left(\frac{Sb^2}{2} + \frac{qa^2}{2k_c}\right) \ln(b), \quad (70)$$

$$F_n = f_n b^{12n} B_n, \quad (71)$$

and

$$E_n = g_n B_n. \quad (72)$$

The quantities, f_n and g_n , appearing in equations (71) and (72) are given by

$$f_n = (1/4) \left[(1-\kappa)(1+\kappa_w) + (1+\kappa)(1-\kappa_w)(a/b)^{12n} \right] \quad (73)$$

and

$$g_n = (1/4) \left[(1+\kappa)(1+\kappa_w) + (1-\kappa)(1-\kappa_w)(a/b)^{12n} \right], \quad (74)$$

respectively, with the definition, $\kappa = k_w/k_c$. Accordingly, the slug flow coolant temperature field of equation (54) reduces to

$$T(r, \phi) = H(r) + \sum_{n=1}^{\infty} \left(g_n r^{6n} + f_n b^{12n} r^{-6n} \right) B_n \cos(6n\phi) \quad (75)$$

wherein the definition,

$$H(r) = A_0 + \frac{S}{4} (r^2 - b^2) - \frac{qa^2}{2k_w} \ln \left(\frac{b}{a} \right) - \left(\frac{Sb^2}{2} + \frac{qa^2}{2k_c} \right) \ln \left(\frac{r}{b} \right) \quad (76)$$

has been used.

The coefficients, B_n , appearing in equation (75) are now determined by means of the homogeneous Neumann boundary condition of equation (17). The arbitrary constant, A_0 , in equation (76) is not found through the application of the boundary condition of equation (17) as it remains arbitrary until a temperature normalization is chosen. This could be, for example, the bulk mean temperature of the coolant. Combining equations (17) and (75) produces, after algebraic manipulation, the relation,

$$\sum_{n=1}^{\infty} \left\{ f_n \left(\frac{b}{r} \right)^{6n} \cos[(6n+1)\phi] - g_n \left(\frac{r}{b} \right)^{6n} \cos[(6n-1)\phi] \right\} 6nb^{6n} B_n \quad (77)$$

$$= r \cos \phi H'(r) .$$

Evaluation of equation (77) on the line $r = c/\cos \phi$ gives

$$\sum_{n=1}^{\infty} \left\{ f_n \left(\frac{b}{c} \right)^{12n} \cos^{6n+1}(\phi) \cos[(6n+1)\phi] - g_n \cos^{1-6n}(\phi) \cos[(6n-1)\phi] \right\} Y_n = \quad (78)$$

$$= \frac{Sk_c c^2}{qa^2} - \left(1 + \frac{Sk_c b^2}{qa^2} \right) \cos^2(\phi)$$

in which the dimensionless coefficients, Y_n , are given by

$$Y_n = \left(\frac{c}{b} \right)^{6n} \frac{6n b^{6n} B_n}{(qa^2/2kc)} . \quad (79)$$

From equation (52) we have

$$Sk_c/q = \pi a^2 u_p/w . \quad (80)$$

In the slug flow coolant case the entire coolant mass flow rate for a single tube in the tube bundle is

$$w = 12u_p \int_0^{\pi/6} d\phi \int_b^{c/\cos(\phi)} r dr = u_p (2\sqrt{3} c^2 - \pi b^2) . \quad (81)$$

Hence, we find from equations (80) and (81) that

$$\frac{Sk_c}{q} = \left(\frac{a}{b}\right)^2 \left[\frac{2\sqrt{3}}{\pi} \left(\frac{c}{b}\right)^2 - 1 \right]^{-1}. \quad (82)$$

Equation (78) can not be satisfied exactly at all points on the line $r = c/\cos \phi$, but only at a finite number. Satisfying equation (78) at N equally spaced points such that $\phi_j = (j-1)\pi/[(N-1)6]$ for $j = 1, 2, 3, \dots, N$ results, when use is made of equation (82), in a set of N linear, inhomogeneous algebraic equations for the first N coefficients, Y_n . This set is

$$\sum_{n=1}^N M_{jn} Y_n = I_j \quad (j = 1, 2, 3, \dots, N) \quad (83)$$

in which the matrix elements M_{jn} are

$$\begin{aligned} M_{jn} = f_n \left(\frac{b}{c}\right)^{12n} \cos^{6n+1} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(6n+1)(j-1)\pi}{(N-1)6} \right] - \\ - g_n \cos^{1-6n} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(6n-1)(j-1)\pi}{(N-1)6} \right]. \end{aligned} \quad (84)$$

The inhomogeneous terms of equation (83) are given by

$$I_j = \left(\frac{c}{b}\right)^2 \frac{\left(\pi - \sqrt{3} \left\{ 1 + \cos \left[\frac{(j-1)\pi}{(N-1)3} \right] \right\} \right)}{[2\sqrt{3} (c/b)^2 - \pi]} \quad (j = 1, 2, 3, \dots, N) \quad (85)$$

It will be noted that the coefficients, Y_n , obtained from equation (83) are functions of four dimensionless parameters: (1) the ratio, κ_w , of the fuel region thermal conductivity to that of the tube wall; (2) the ratio, κ , of the tube wall thermal conductivity to that of the coolant; (3) the ratio, a/b , of the inside tube wall radius to the outside radius; and (4) the inverse pitch-to-diameter ratio, b/c , of the tube bundle.

4.2 Coolant in Laminar Flow

In the case of a laminar flow coolant, equations (65)-(68), relating c_0 , d_0 , c_n , and d_n to A_0 and B_n , remain valid. Upon introducing the definition,

$$H_L(r) = -\frac{\sqrt{3} r^2}{4\pi} + \frac{\sqrt{3} r^2}{4\pi} \ln\left(\frac{r}{b}\right) - \frac{r^4}{64c^2} + \frac{r^2 b^2}{16c^2} \quad (86)$$

into equation (62) and upon substituting equations (29) and (62) into the outside wall surface boundary conditions of equations (13) and (14), we obtain

$$\begin{aligned} E_0^L + F_0^L \ln(b) + \frac{\pi a^2 q H_L(b)}{12k_c c^2 M} + \sum_{n=1}^{\infty} \left(E_n^L b^{6n} + F_n^L b^{-6n} \right) \cos(6n\phi) + \\ + \frac{\pi a^2 g}{12k_c c^2 M} \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{b^{6n+2}}{c^{6n(6n+1)}} + \frac{b^{6n+2}}{c^{6n(6n-1)}} \right] \cos(6n\phi) = \\ A_0 - \frac{qa^2}{2k_w} \ln\left(\frac{b}{a}\right) + \sum_{n=1}^{\infty} \frac{a^{6n} B_n}{2} \left[(1+\kappa_w) \left(\frac{b}{a}\right)^{6n} + (1-\kappa_w) \left(\frac{a}{b}\right)^{6n} \right] \cos(6n\phi) \end{aligned} \quad (87)$$

together with

$$\begin{aligned}
& \frac{F_0^L}{b} + \frac{\pi a^2 q H_L'(b)}{12k_c c^2 M} + \sum_{n=1}^{\infty} (6n) \left(E_n^L b^{6n-1} - F_n^L b^{-6n-1} \right) \cos(6n\phi) + \\
& + \frac{\pi a^2 q}{12k_c c^2 M} \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(6n+2)b^{6n+1}}{c^{6n}(6n+1)} + \frac{(2-6n)b^{6n+1}}{c^{6n}(6n-1)} \right] \cos(6n\phi) = \quad (88) \\
& = -\frac{qa^2 \kappa}{2k_w b} + \sum_{n=1}^{\infty} \frac{a^{6n} B_n \kappa}{2} \left[6n(1+\kappa_w) \frac{b^{6n-1}}{a^{6n}} - 6n(1-\kappa_w) \frac{a^{6n}}{b^{6n+1}} \right] \cos(6n\phi) .
\end{aligned}$$

From equations (87) and (88) it is found by the procedure which follows equation (64) that

$$F_0^L = -\frac{qa^2 \kappa}{2k_w} - \frac{\pi a^2 q b H_L'(b)}{12k_c c^2 M} , \quad (89)$$

$$E_0^L = A_0 - \frac{\pi a^2 q H_L(b)}{12k_c c^2 M} - \frac{qa^2}{2k_w} \ln\left(\frac{b}{a}\right) + \left[\frac{qa^2 \kappa}{2k_w} + \frac{\pi a^2 q b H_L'(b)}{12k_c c^2 M} \right] \ln(b) , \quad (90)$$

$$E_n^L = g_n B_n - \frac{\pi a^2 q}{12k_c M} \left(\frac{b}{c}\right)^2 \frac{\Delta_n}{c^{6n} 24n(6n-1)} , \quad (91)$$

and

$$F_n^L = f_n B_n b^{12n} - \frac{\pi a^2 q}{12k_c M} \left(\frac{b}{c}\right)^2 \frac{\Delta_n b^{12n}}{c^{6n} 24n(6n+1)} . \quad (92)$$

In equations (91) and (92), g_n and f_n have been previously defined in equations (73) and (74). Accordingly, the coolant temperature field in the laminar flow case as given in equation (62) becomes

$$\begin{aligned}
 T(r, \phi) = & E_0^L + F_0^L \ln(r) + \frac{\pi a^2 q H_L(r)}{12 k_c M c^2} + \sum_{n=1}^{\infty} \left(g_n r^{6n} + f_n \frac{b^{12n}}{r^{6n}} \right) B_n \cos(6n\phi) - \\
 & - \frac{\pi a^2 q}{12 k_c M} \left(\frac{b}{c} \right)^2 \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(r/c)^{6n}}{6n-1} + \left(\frac{b}{c} \right)^{6n} \frac{(b/r)^{6n}}{6n+1} \right] \cos(6n\phi) + \quad (93) \\
 & + \frac{\pi a^2 q}{12 k_c M} \left(\frac{r}{c} \right)^2 \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(r/c)^{6n}}{6n+1} + \left(\frac{b}{c} \right)^{6n} \frac{(b/r)^{6n}}{6n-1} \right] \cos(6n\phi) .
 \end{aligned}$$

The relation,

$$\begin{aligned}
 & \left[F_0^L + \pi a^2 q r H_L'(r) \right] \cos(\phi) + \\
 & + \sum_{n=1}^{\infty} 6n b^{6n} B_n \left\{ g_n (r/b)^{6n} \cos[(6n-1)\phi] - f_n (b/r)^{6n} \cos[(6n+1)\phi] \right\} - \\
 & - \frac{\pi a^2 q}{12 k_c c^2 M} \sum_{n=1}^{\infty} \frac{\Delta_n b^2}{4} \left\{ \frac{(r/c)^{6n} \cos[(6n-1)\phi]}{6n-1} - \frac{(b/c)^{6n} (b/r)^{6n} \cos[(6n+1)\phi]}{6n+1} \right\} + \quad (94) \\
 & + \frac{\pi a^2 q}{12 k_c c^2 M} \sum_{n=1}^{\infty} \frac{\Delta_n r^2}{24n} \left(\frac{(r/c)^{6n}}{6n+1} \left\{ 6n \cos[(6n-1)\phi] + 2 \cos(\phi) \cos(6n\phi) \right\} - \right. \\
 & \left. - \left(\frac{b}{c} \right)^{6n} \left(\frac{b}{r} \right)^{6n} \frac{1}{6n-1} \left\{ 6n \cos[(6n+1)\phi] - 2 \cos(\phi) \cos(6n\phi) \right\} \right) = 0 ,
 \end{aligned}$$

follows when equation (93) is substituted into equation (17). Evaluating equation (94) on the line $r = c/\cos\phi$ together with the use of equation (89) for F_0^L and equation (86), from which the derivative, $H_L'(r)$, is obtained, yields

$$\begin{aligned}
& \sum_{n=1}^{\infty} \left\{ f_n (b/c)^{12n} \cos^{6n+1}(\phi) \cos[(6n+1)\phi] - g_n \cos^{1-6n}(\phi) \cos[(6n-1)\phi] \right\} x_n = \\
& - \frac{\sqrt{3}}{4\pi} + \frac{\sqrt{3}}{2\pi} \ln \left[\frac{c}{b \cos(\phi)} \right] + \frac{1}{8} \left(\frac{b}{c} \right)^2 - \frac{1}{16 \cos^2 \phi} + \\
& + \left[\frac{\sqrt{3}}{4\pi} \left(\frac{b}{c} \right)^2 - \frac{6M}{\pi} - \frac{1}{16} \left(\frac{b}{c} \right)^4 \right] \cos^2(\phi) + \\
& + \sum_{v=1}^{\infty} \Delta_v \left(\frac{(b/c)^{12v+2}}{4(6v+1)} \cos^{6v+1}(\phi) \cos[(6v+1)\phi] - \right. \\
& - \left(\frac{b}{c} \right)^2 \frac{\cos^{1-6v}(\phi) \cos[(6v-1)\phi]}{4(6v-1)} + \\
& + \frac{1}{4(6v+1) \cos^{6v+1}(\phi)} \left\{ \cos[(6v-1)\phi] + \frac{1}{3v} \cos(\phi) \cos(6v\phi) \right\} - \\
& - \left(\frac{b}{c} \right)^{12v} \frac{\cos^{6v-1}(\phi)}{4(6v-1)} \left\{ \cos[(6v+1)\phi] - \frac{1}{3v} \cos(\phi) \cos(6v\phi) \right\} \Bigg) \quad (95)
\end{aligned}$$

in which the definition,

$$x_n = \frac{6nb^{6n} B_n (c/b)^{6n}}{\pi a^2 q / 12k_c M} \quad (96)$$

has been introduced. When equation (95) is satisfied at N equally spaced points, $\phi_j = (j-1)\pi/[(N-1)6]$, the resulting set of N linear, inhomogeneous algebraic equations for the coefficients, χ_n , is

$$\sum_{n=1}^N M_{jn} \chi_n = K_j \quad (j = 1, 2, 3, \dots, N) \quad (97)$$

The matrix elements, M_{jn} , which arise in equation (97) for this laminar flow coolant case are the same as those which appeared in the slug flow coolant case and are given in equation (84), while the inhomogeneous terms, K_j , in equation (97) are, for $j = 1, 2, 3, \dots, N$, given by

$$\begin{aligned} K_j = & -\frac{\sqrt{3}}{4\pi} + \frac{\sqrt{3}}{2\pi} \ln \left\{ c/b \cos \left[\frac{(j-1)\pi}{(N-1)6} \right] \right\} + \frac{1}{8} \left(\frac{b}{c} \right)^2 - \frac{1}{16 \cos^2 \left[\frac{(j-1)\pi}{(N-1)6} \right]} + \\ & + \left[\frac{\sqrt{3}}{4\pi} \left(\frac{b}{c} \right)^2 - \frac{6M}{\pi} - \frac{1}{16} \left(\frac{b}{c} \right)^4 \right] \cos^2 \left[\frac{(j-1)\pi}{(N-1)6} \right] + \\ & + \sum_{v=1}^N \Delta_v \left(\frac{(b/c)^{12v+2}}{4(6v+1)} \cos^{6v+1} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(6v+1)(j-1)\pi}{(N-1)6} \right] - \right. \\ & - \frac{(b/c)^2}{4(6v-1)} \cos^{1-6v} \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(6v-1)(j-1)\pi}{(N-1)6} \right] + \\ & + \frac{1}{4(6v+1)} \cos^{-1-6v} \left[\frac{(j-1)\pi}{(N-1)6} \right] \left\{ \cos \left[\frac{(6v-1)(j-1)\pi}{(N-1)6} \right] + \frac{1}{3v} \cos \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(j-1)v\pi}{(N-1)} \right] \right\} - \\ & - \frac{(b/c)^{12v}}{4(6v-1)} \cos^{6v-1} \left[\frac{(j-1)\pi}{(N-1)6} \right] \left\{ \cos \left[\frac{(6v+1)(j-1)\pi}{(N-1)6} \right] - \frac{1}{3v} \cos \left[\frac{(j-1)\pi}{(N-1)6} \right] \cos \left[\frac{(j-1)v\pi}{(N-1)} \right] \right\} \Bigg) \end{aligned} \quad (98)$$

The expansion coefficients, χ_n , sought in the solution of equation (97) are functions of the same four dimensionless parameters as are coefficients, Y_n , in equation (83).

With equations (83) and (97) the problem of determining the temperature fields in each of the three regions of the tube bundle composite domain shown in Fig. 1 has been reduced to a problem in matrix inversion for the slug flow and the laminar flow coolant cases, respectively.

5. ANALYTICAL AND NUMERICAL RESULTS FOR THE TEMPERATURE FIELDS AND THE HEAT FLUXES

5.1 Coolant in Slug Flow

With equations (25) and (79), the fuel region temperature field when the coolant is in slug flow is found to be

$$v(r, \phi) = A_0 + \frac{qa^2}{4k} \left[1 - \left(\frac{r}{a} \right)^2 \right] + \frac{qa^2}{2k_c} \sum_{n=1}^{\infty} \frac{Y_n}{6n} \left(\frac{b}{c} \right)^{6n} \left(\frac{r}{b} \right)^{6n} \cos(6n\phi) \quad (99)$$

in which the Y_n are solutions of the set, equation (83). From equations (29), (65)-(68), and (79) the tube wall temperature field is

$$t(r, \phi) = A_0 - \frac{qa^2}{2k_w} \ln \left(\frac{r}{a} \right) + \frac{qa^2}{2k_c} \sum_{n=1}^{\infty} \frac{Y_n}{12n} \left(\frac{b}{c} \right)^{6n} \left[(1+\kappa_w) \left(\frac{r}{b} \right)^{6n} + (1-\kappa_w) \left(\frac{a}{b} \right)^{6n} \left(\frac{a}{r} \right)^{6n} \right] \cos(6n\phi) . \quad (100)$$

The slug flow coolant temperature field is

$$\begin{aligned}
T(r, \phi) = & A_0 + \frac{S}{4} (r^2 - b^2) - \frac{qa^2}{2k_w} \ln \left(\frac{b}{a} \right) - \left[\frac{Sb^2}{2} + \frac{qa^2}{2k_c} \right] \ln \left(\frac{r}{b} \right) + \\
& + \frac{qa^2}{2k_c} \sum_{n=1}^{\infty} \frac{Y_n}{6n} \left(\frac{b}{c} \right)^{6n} \left[g_n \left(\frac{r}{b} \right)^{6n} + f_n \left(\frac{b}{r} \right)^{6n} \right] \cos(6n\phi)
\end{aligned} \tag{101}$$

where equations (75), (76), and (79) have been combined.

In equations (99)-(101) the constant, A_0 , remains arbitrary until a temperature normalization has been assigned. For example, if T_m is the bulk mean coolant temperature of the coolant in slug flow, then A_0 is related to the bulk mean coolant temperature through

$$\begin{aligned}
\frac{T_m - A_0}{qa^2/2k_c} = & \frac{3}{2\pi} \left[\frac{10}{9\sqrt{3}} - \frac{\pi}{6} \left(\frac{b}{c} \right)^4 \right] \left[\frac{2\sqrt{3}}{\pi} - \left(\frac{b}{c} \right)^2 \right]^{-2} - \frac{k_c}{k_w} \ln \left(\frac{b}{a} \right) - \frac{1}{2} \left(\frac{b}{c} \right)^2 \left[\frac{2\sqrt{3}}{\pi} - \left(\frac{b}{c} \right)^2 \right]^{-1} - \\
& - \frac{24\sqrt{3}}{\pi^2} \left[\frac{2\sqrt{3}}{\pi} - \left(\frac{b}{c} \right)^2 \right]^{-2} \left[\frac{1}{2\sqrt{3}} \ln \left(\frac{2c}{\sqrt{3}b} \right) + \frac{\pi}{12} - \frac{\sqrt{3}}{4} + \frac{\pi}{24} \left(\frac{b}{c} \right)^2 \right] + \\
& + \frac{12}{\pi} \left[\frac{2\sqrt{3}}{\pi} - \left(\frac{b}{c} \right)^2 \right]^{-1} \sum_{n=1}^{\infty} \frac{Y_n}{6n} \left[\frac{g_n}{6n+2} - \frac{f_n}{6n-2} \right] \left(\frac{b}{c} \right)^{12n}.
\end{aligned} \tag{102}$$

From equation (99), A_0 is related to the hottest point on the inside wall surface by

$$v(a, 0) = A_0 + \left(qa^2/2k_c \right) \sum_{n=1}^{\infty} (Y_n/6n) (a/c)^{6n}. \tag{103}$$

Subtracting equation (102) from equation (103) gives a relation for the highest temperature on the inside wall surface directly in terms of the bulk mean coolant temperature.

The circumferential variation of the inside wall temperature normalized to its hot point at $\phi = 0$ is obtained from equation (100) in the dimensionless form,

$$\frac{t(a,0) - t(a,\phi)}{(qa^2/2k_c)} = \sum_{n=1}^{\infty} \frac{Y_n}{3n} \left(\frac{a}{b}\right)^{6n} \left(\frac{b}{c}\right)^{6n} \sin^2(3n\phi) . \quad (104)$$

The outside wall temperature normalized to its hot point has the circumferential variation given by

$$\frac{t(b,0) - t(b,\phi)}{(qa^2/2k_c)} = \sum_{n=1}^{\infty} \frac{Y_n}{6n} \left(\frac{b}{c}\right)^{6n} \left[(1+\kappa_w) + (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \sin^2(3n\phi) . \quad (105)$$

The angular dependence of the tube wall temperature drop is

$$\begin{aligned} \frac{t(a,\phi) - t(b,\phi)}{(qa^2/2k_c)} &= \frac{1}{\kappa} \ln \left(\frac{b}{a}\right) + \\ &+ \sum_{n=1}^{\infty} \frac{Y_n}{6n} \left(\frac{b}{c}\right)^{6n} \left\{ \left(\frac{a}{b}\right)^{6n} - \frac{1}{2} \left[(1+\kappa_w) + (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \right\} \cos(6n\phi) . \end{aligned} \quad (106)$$

From equation (100) we find that the angular dependence of the inside wall heat flux is

$$\frac{-k_w \frac{\partial t}{\partial r}(a, \phi)}{(qa/2)} = 1 - \kappa \kappa_w \sum_{n=1}^{\infty} Y_n \left(\frac{a}{b}\right)^{6n} \left(\frac{b}{c}\right)^{6n} \cos(6n\phi) \quad (107)$$

where $qa/2$ is the average value of the inside wall heat flux. The circumferential variation of the outside wall heat flux is

$$\frac{-k_w \frac{\partial t}{\partial r}(b, \phi)}{(qa^2/2b)} = 1 - \kappa \sum_{n=1}^{\infty} \frac{Y_n}{2} \left(\frac{b}{c}\right)^{6n} \left[(1+\kappa_w) - (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \cos(6n\phi) \quad (108)$$

in which $qa^2/2b$ is the average outside wall heat flux.

5.2 Coolant in Laminar Flow

When the coolant is in laminar flow, the fuel region temperature field is found from equations (25) and (96) to be

$$v(r, \phi) = A_0 + \frac{qa^2}{4k} \left[1 - \left(\frac{r}{a}\right)^2 \right] + \frac{\pi a^2 q}{12k_c M} \sum_{n=1}^{\infty} \frac{X_n}{6n} \left(\frac{b}{c}\right)^{6n} \left(\frac{r}{b}\right)^{6n} \cos(6n\phi) \quad (109)$$

Combining equations (29), (65)-(68), and (96) produces the tube wall temperature field for a laminar flow coolant in the form,

$$t(r, \phi) = A_0 - \frac{qa^2}{2k_w} \ln \left(\frac{r}{a}\right) + \frac{\pi a^2 q}{12k_c M} \sum_{n=1}^{\infty} \frac{X_n}{12n} \left(\frac{b}{c}\right)^{6n} \left(\frac{a}{b}\right)^{6n} \left[(1+\kappa_w) \left(\frac{r}{a}\right)^{6n} + (1-\kappa_w) \left(\frac{a}{r}\right)^{6n} \right] \cos(6n\phi) \quad (110)$$

The coolant temperature field for the laminar flow coolant case is given by

$$\begin{aligned}
T(r, \phi) = & A_0 - \frac{qa^2}{2k_w} \ln \left(\frac{b}{a} \right) - \left[\frac{qa^2}{2k_c} + \frac{\pi a^2 q}{12k_c M} \frac{bH'_L(b)}{c^2} \right] \ln \left(\frac{r}{b} \right) + \\
& + \frac{\pi a^2 q}{12k_c M c^2} \left[H_L(r) - H_L(b) \right] + \frac{\pi a^2 q}{12k_c M} \sum_{n=1}^{\infty} \frac{\chi_n}{6n} \left(\frac{b}{c} \right)^{6n} \left[g_n \left(\frac{r}{b} \right)^{6n} + f_n \left(\frac{b}{r} \right)^{6n} \right] \cos(6n\phi) - \\
& - \frac{\pi a^2 q}{12k_c M} \left(\frac{b}{c} \right)^2 \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(r/c)^{6n}}{6n-1} + \left(\frac{b}{c} \right)^{6n} \frac{(b/r)^{6n}}{6n+1} \right] \cos(6n\phi) + \\
& + \frac{\pi a^2 q}{12k_c M} \left(\frac{r}{c} \right)^2 \sum_{n=1}^{\infty} \frac{\Delta_n}{24n} \left[\frac{(r/c)^{6n}}{6n+1} + \left(\frac{b}{c} \right)^{6n} \frac{(b/r)^{6n}}{6n-1} \right] \cos(6n\phi)
\end{aligned} \tag{111}$$

which is obtained from equations (89), (90), and (93) and in which $H_L(r)$ is defined by equation (86). Again, in equations (109)-(111) the constant A_0 is arbitrary until a temperature normalization has been selected.

From equation (110) we find the following results:

- (1) Circumferential variation of the inside wall temperature normalized to its hot spot,

$$\frac{t(a, 0) - t(a, \phi)}{(qa^2/2k_c)} = \frac{\pi}{6M} \sum_{n=1}^{\infty} \frac{\chi_n}{3n} \left(\frac{a}{b} \right)^{6n} \left(\frac{b}{c} \right)^{6n} \sin^2(3n\phi); \tag{112}$$

- (2) Circumferential variation of the outside wall temperature normalized to its hot spot,

$$\frac{t(b,0) - t(b,\phi)}{(qa^2/2k_c)} = \frac{\pi}{6M} \sum_{n=1}^{\infty} \frac{\chi_n}{6n} \left(\frac{b}{c}\right)^{6n} \left[(1+\kappa_w) + (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \sin^2(3n\phi); \quad (113)$$

- (3) Circumferential variation of the temperature drop across the wall,

$$\begin{aligned} \frac{t(a,\phi) - t(b,\phi)}{(qa^2/2k_c)} = & \frac{1}{\kappa} \ln \left(\frac{b}{a}\right) + \frac{\pi}{6M} \sum_{n=1}^{\infty} \frac{\chi_n}{6n} \left(\frac{b}{c}\right)^{6n} \left\{ \left(\frac{a}{b}\right)^{6n} - \right. \\ & \left. - \frac{1}{2} \left[(1+\kappa_w) + (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \right\} \cos(6n\phi); \end{aligned} \quad (114)$$

- (4) Circumferential variation of the inside wall heat flux,

$$\frac{-k_w \frac{\partial t}{\partial r}(a,\phi)}{(qa/2)} = 1 - \kappa \kappa_w \frac{\pi}{6M} \sum_{n=1}^{\infty} \chi_n \left(\frac{a}{b}\right)^{6n} \left(\frac{b}{c}\right)^{6n} \cos(6n\phi). \quad (115)$$

where $qa/2$ is the average inside wall heat flux; and

- (5) Circumferential variation of the outside wall heat flux,

$$\frac{-k_w \frac{\partial t}{\partial r}(b,\phi)}{(qa^2/2b)} = 1 - \kappa \frac{\pi}{6M} \sum_{n=1}^{\infty} \frac{\chi_n}{2} \left(\frac{b}{c}\right)^{6n} \left[(1+\kappa_w) - (1-\kappa_w) \left(\frac{a}{b}\right)^{12n} \right] \cos(6n\phi) \quad (116)$$

where $qa^2/2b$ is the average outside wall heat flux.

5.3 Numerical Results

Because the analytical results for the temperature fields and heat fluxes in Sections 5.1 and 5.2 depend upon four parameters, only representative numerical results will be included here. In Table 6 solutions of the set, equation (83), for the slug flow coolant expansion coefficients, Y_n , are tabulated as functions of the diameter-to-pitch ratio, $D/P = b/c$, of the tube bundle with these values of the relevant parameters: (1) outside tube diameter of 0.400 inches and tube wall thickness of 25 mils so that $a/b = 0.875$; (2) $\kappa = k_w/k_c = 1.102$; (3) $\kappa_w = k/k_w = 0.221$, and $N = 8$, i.e., the homogeneous Neumann boundary condition of equation (17) is satisfied at eight points. The laminar flow expansion coefficients, χ_n , obtained upon solving equation (97), are given in Table 7 for these same values of the relevant parameters. Although the algebraic sets, equations (83) and (97), have been solved for $N = 8$, only the first four expansion coefficients are recorded in Tables 6 and 7, as the series in Sections 5.1 and 5.2 converge rapidly.

Immediately following Section 6, the circumferential variations of the inside and outside wall surface temperatures, the tube wall temperature drop, and the inside and outside wall heat fluxes are all tabulated at 3-degree intervals for 25-mil-thick tubes with outside diameters ranging from 0.500 to 0.250 inches in increments of 0.05 inches for the same range and values of the diameter-to-pitch ratio of the tube bundle as appear in Tables 6 and 7 and, also, for the same values of the thermal conductivity ratios quoted above. In conjunction with these tabulations, the following points may be observed:

- (1) The numbers under "laminar flow" are for the laminar flow coolant case and are tabulations of equations (112)-(116) from left to right.
- (2) The numbers under "slug flow" are for the slug flow coolant case and are tabulations of equations (104)-(108) from left to right.
- (3) All numbers in these tabulations are dimensionless, as the analytic results of Sections 5.1 and 5.2 have been expressed in dimensionless form.

TABLE 6

Values of the Slug Flow Coefficients, Y_n , versus the Diameter-to-Pitch Ratio for $a/b = 0.875$, $\kappa = 1.102$, $\kappa_w = 0.221$, and $N = 8$

<u>D/P</u>	<u>Y_1</u>	<u>Y_2</u>	<u>Y_3</u>	<u>Y_4</u>
0.95	0.81550	0.22534(-1)*	0.14221(-2)	0.83002(-4)
0.92	0.63085	0.15090(-1)	0.80928(-3)	0.47809(-4)
0.89	0.51708	0.11019(-1)	0.49099(-3)	0.27900(-4)
0.86	0.44028	0.85857(-2)	0.31494(-3)	0.16609(-4)
0.83	0.38513	0.70344(-2)	0.21344(-3)	0.10099(-4)
0.80	0.34370	0.59921(-2)	0.15306(-3)	0.63059(-5)
0.75	0.29379	0.48848(-2)	0.99674(-4)	0.31125(-5)
0.50	0.18580	0.29619(-2)	0.46267(-4)	0.73495(-6)

TABLE 7

Values of the Laminar Flow Coefficients, X_n , versus the Diameter-to-Pitch Ratio for $a/b = 0.875$, $\kappa = 1.102$, $\kappa_w = 0.221$, and $N = 8$

<u>D/P</u>	<u>X_1</u>	<u>X_2</u>	<u>X_3</u>	<u>X_4</u>
0.95	0.96473(-3)*	-0.11380(-3)	0.44573(-5)	0.10615(-5)
0.92	0.14859(-2)	-0.11748(-3)	0.46832(-6)	0.65881(-6)
0.89	0.21075(-2)	-0.10985(-3)	-0.17260(-5)	0.33926(-6)
0.86	0.28188(-2)	-0.95182(-4)	-0.25753(-5)	0.15891(-6)
0.83	0.36130(-2)	-0.76934(-4)	-0.26534(-5)	0.73370(-7)
0.80	0.44878(-2)	-0.57251(-4)	-0.23565(-5)	0.37810(-7)
0.75	0.61310(-2)	-0.23709(-4)	-0.15927(-5)	0.27214(-7)
0.50	0.18950(-1)	0.18227(-3)	0.21254(-5)	0.83949(-7)

* The number in parentheses is the power of ten that gives the order of magnitude, e.g., $-1.320(3) = -1.320 \times 10^3$.

(4) For a 25-mil tube wall the correspondence between the outside tube diameter and dimensionless input parameter, a/b , is this:

Tube O.D. (inches)	0.500	0.450	0.400	0.350	0.300	0.250
a/b	0.900	0.889	0.875	0.857	0.833	0.800

(5) "Temperatures for order 8" means that the boundary condition of equation (17) was satisfied at eight points on the line $r = c/\cos(\phi)$.

(6) Orders of magnitude are indicated by the final characters of each tabulated entry, e.g., $E-02 = 10^{-2}$.

It will be noted that the circumferential variations of the inside and outside tube wall temperatures and tube wall temperature drop are larger when the coolant is in laminar flow than when it is in slug flow. Also, these variations are more sensitive to the pitch-to-diameter ratio of the tube bundle in the laminar flow coolant case than in the slug flow coolant case. The circumferential variation in the outside tube wall temperature is more pronounced than that in the inside wall temperature. The same behavior is also found when the inside and outside wall heat fluxes are compared. As the pitch-to-diameter ratio of the tube is increased, the inside and outside wall heat fluxes become uniform to within a fraction of a percent of the average heat flux when the pitch-to-diameter ratio reaches a value of two.

6. CONCLUSIONS

A coupled, multiregion analysis of the fully developed temperature and velocity fields occurring in triangular tube bundles with internal, solid nuclear heat sources has been presented. Analytical expressions for the temperature and velocity fields have been obtained by the method of finite Fourier cosine transforms in the form of infinite series representations. These series are truncated at N terms, when N is the number of points at which the homogeneous Neumann boundary conditions of equations (16) and (17) are satisfied. The expansion coefficients appearing in the series for the velocity and temperature fields have been obtained by matrix inversion.

Solving out the fundamental energy and momentum balances in analytic form has resulted in computing codes with short execution times. For example, for 48 sets of the four input parameters, κ , κ_w , a/b , and b/c , the execution time on the IBM-7094 is 2.99 minutes, i.e., 3.74 seconds per set. In this time the circumferential variations in the inside and outside tube wall surface temperatures, the tube wall temperature drop, and the inside and outside tube wall heat fluxes at 3-degree intervals are obtained for N ranging from $N = 2$ to $N = 8$ in increments of one for both the slug flow and laminar flow coolant cases. Also, the solutions of the algebraic sets, equations (42), (83), and (97) are found.

TABULATIONS OF THE CIRCUMFERENTIAL VARIATIONS IN THE
INSIDE AND OUTSIDE TUBE WALL TEMPERATURES, THE
TUBE WALL TEMPERATURE DROP, AND THE INSIDE AND
OUTSIDE TUBE WALL HEAT FLUXES

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.578696E-01	0.839757E 00	0.350243E-00
3	0.515232E-02	0.660807E-02	0.593253E-01	0.846658E 00	0.373913E-00
6	0.202245E-01	0.260307E-01	0.636757E-01	0.867014E 00	0.445065E-00
9	0.440602E-01	0.570388E-01	0.708482E-01	0.899729E 00	0.563847E 00
12	0.747342E-01	0.974980E-01	0.806333E-01	0.942771E 00	0.728969E 00
15	0.109592E-00	0.144258E-00	0.925361E-01	0.992956E 00	0.934343E 00
18	0.145371E-00	0.193126E-00	0.105624E-00	0.104584E 01	0.116516E 01
21	0.178456E-00	0.239083E-00	0.118497E-00	0.109594E 01	0.139640E 01
24	0.205266E-00	0.276849E-00	0.129453E-00	0.113735E 01	0.159590E 01
27	0.222740E-00	0.301706E-00	0.136835E-00	0.116471E 01	0.173149E 01
30	0.228809E-00	0.310382E-00	0.139442E-00	0.117429E 01	0.177958E 01
SLUG FLOW					
0	-0.	-0.	0.757866E-01	0.919515E 00	0.651019E 00
3	0.273282E-02	0.378019E-02	0.768340E-01	0.923623E 00	0.669790E 00
6	0.106410E-01	0.146938E-01	0.798395E-01	0.935474E 00	0.723497E 00
9	0.228918E-01	0.315290E-01	0.844239E-01	0.953729E 00	0.804991E 00
12	0.382166E-01	0.524734E-01	0.900434E-01	0.976392E 00	0.904222E 00
15	0.550632E-01	0.753608E-01	0.960843E-01	0.100109E 01	0.101014E 01
18	0.717667E-01	0.979245E-01	0.101944E-00	0.102538E 01	0.111222E 01
21	0.867169E-01	0.118020E-00	0.107089E-00	0.104695E 01	0.120135E 01
24	0.985042E-01	0.133802E-00	0.111084E-00	0.106385E 01	0.127027E 01
27	0.106037E-00	0.143861E-00	0.113611E-00	0.107460E 01	0.131373E 01
30	0.108626E-00	0.147314E-00	0.114475E-00	0.107829E 01	0.132857E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.92$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.686577E-01	0.887206E 00	0.532681E 00
3	0.369281E-02	0.484940E-02	0.698143E-01	0.892349E 00	0.552111E 00
6	0.144588E-01	0.190313E-01	0.732302E-01	0.907414E 00	0.609739E 00
9	0.313732E-01	0.414450E-01	0.787295E-01	0.931302E 00	0.703254E 00
12	0.529411E-01	0.702599E-01	0.859765E-01	0.962141E 00	0.827811E 00
15	0.771833E-01	0.102958E-00	0.944323E-01	0.997300E 00	0.974889E 00
18	0.101779E-00	0.136460E-00	0.103339E-00	0.103349E 01	0.113162E 01
21	0.124270E-00	0.167378E-00	0.111765E-00	0.106703E 01	0.128136E 01
24	0.142326E-00	0.192384E-00	0.118716E-00	0.109426E 01	0.140585E 01
27	0.154015E-00	0.208658E-00	0.123301E-00	0.111202E 01	0.148838E 01
30	0.158060E-00	0.214305E-00	0.124903E-00	0.111819E 01	0.151729E 01
SLUG FLOW					
0	-0.	-0.	0.831480E-01	0.949212E 00	0.781051E 00
3	0.171678E-02	0.235870E-02	0.837899E-01	0.951769E 00	0.792464E 00
6	0.668957E-02	0.918077E-02	0.856392E-01	0.959160E 00	0.825283E 00
9	0.144070E-01	0.197395E-01	0.884804E-01	0.970588E 00	0.875538E 00
12	0.240842E-01	0.329323E-01	0.919960E-01	0.984845E 00	0.937454E 00
15	0.347513E-01	0.474170E-01	0.958137E-01	0.100047E 01	0.100438E 01
18	0.453567E-01	0.617619E-01	0.995533E-01	0.101592E 01	0.106964E 01
21	0.548723E-01	0.745882E-01	0.102864E-00	0.102970E 01	0.112718E 01
24	0.623900E-01	0.846931E-01	0.105451E-00	0.104055E 01	0.117202E 01
27	0.672011E-01	0.911474E-01	0.107094E-00	0.104747E 01	0.120044E 01
30	0.688561E-01	0.933655E-01	0.107607E-00	0.104984E 01	0.121016E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.89$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.767534E-01	0.921762E 00	0.671655E 00
3	0.258846E-02	0.344897E-02	0.776139E-01	0.925448E 00	0.686396E 00
6	0.101192E-01	0.135008E-01	0.801350E-01	0.936201E 00	0.729681E 00
9	0.219040E-01	0.292831E-01	0.841325E-01	0.953110E 00	0.798608E 00
12	0.368499E-01	0.493887E-01	0.892922E-01	0.974699E 00	0.888081E 00
15	0.535425E-01	0.719606E-01	0.951716E-01	0.998996E 00	0.990676E 00
18	0.703663E-01	0.948310E-01	0.101218E-00	0.102368E 01	0.109684E 01
21	0.856556E-01	0.115717E-00	0.106815E-00	0.104627E 01	0.119565E 01
24	0.978648E-01	0.132464E-00	0.111352E-00	0.106442E 01	0.127609E 01
27	0.105739E-00	0.143294E-00	0.114309E-00	0.107618E 01	0.132867E 01
30	0.108458E-00	0.147041E-00	0.115336E-00	0.108024E 01	0.134695E 01
SLUG FLOW					
0	-0.	-0.	0.873192E-01	0.966133E 00	0.854524E 00
3	0.114158E-02	0.156181E-02	0.877394E-01	0.967823E 00	0.861958E 00
6	0.445026E-02	0.608406E-02	0.88953CE-01	0.972715E 00	0.883401E 00
9	0.959094E-02	0.130976E-01	0.908259E-01	0.980296E 00	0.916421E 00
12	0.160468E-01	0.218844E-01	0.931568E-01	0.989784E 00	0.957400E 00
15	0.231754E-01	0.315604E-01	0.957043E-01	0.100022E 01	0.100204E 01
18	0.302751E-01	0.411711E-01	0.982152E-01	0.101057E 01	0.104591E 01
21	0.366556E-01	0.497868E-01	0.100450E-00	0.101984E 01	0.108485E 01
24	0.417031E-01	0.565886E-01	0.102205E-00	0.102715E 01	0.111534E 01
27	0.449364E-01	0.609395E-01	0.103322E-00	0.103182E 01	0.113473E 01
30	0.460491E-01	0.624358E-01	0.103706E-00	0.103343E 01	0.114138E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.86$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.825126E-01	0.945921E 00	0.771395E 00
3	0.179966E-02	0.241775E-02	0.831307E-01	0.948515E 00	0.782094E 00
6	0.702933E-02	0.945007E-02	0.849334E-01	0.956065E 00	0.813336E 00
9	0.151950E-01	0.204496E-01	0.877672E-01	0.967884E 00	0.862558E 00
12	0.255194E-01	0.343901E-01	0.913833E-01	0.982880E 00	0.925548E 00
15	0.370096E-01	0.499470E-01	0.954500E-01	0.999636E 00	0.996619E 00
18	0.485474E-01	0.656120E-01	0.995773E-01	0.101653E 01	0.106898E 01
21	0.589963E-01	0.798356E-01	0.103352E-00	0.103189E 01	0.113536E 01
24	0.673160E-01	0.911849E-01	0.106382E-00	0.104416E 01	0.118875E 01
27	0.726702E-01	0.985001E-01	0.108342E-00	0.105207E 01	0.122337E 01
30	0.745175E-01	0.101026E-00	0.109021E-00	0.105481E 01	0.123536E 01
SLUG FLOW					
0	-0.	-0.	0.899000E-01	0.976641E 00	0.899896E 00
3	0.785926E-03	0.107235E-02	0.901865E-01	0.977800E 00	0.904947E 00
6	0.306467E-02	0.417949E-02	0.910149E-01	0.981158E 00	0.919543E 00
9	0.660771E-02	0.900456E-02	0.922969E-01	0.986369E 00	0.942099E 00
12	0.110616E-01	0.150599E-01	0.938983E-01	0.992905E 00	0.970219E 00
15	0.159850E-01	0.217408E-01	0.956559E-01	0.100011E 01	0.100101E 01
18	0.208942E-01	0.283894E-01	0.973953E-01	0.100727E 01	0.103142E 01
21	0.253108E-01	0.343601E-01	0.989494E-01	0.101370E 01	0.105853E 01
24	0.288077E-01	0.390805E-01	0.100173E-00	0.101877E 01	0.107983E 01
27	0.310492E-01	0.421029E-01	0.100954E-00	0.102202E 01	0.109342E 01
30	0.318209E-01	0.431428E-01	0.101222E-00	0.102314E 01	0.109808E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.865222E-01	0.962577E 00	0.841177E 00
3	0.124934E-02	0.168600E-02	0.869588E-01	0.964390E 00	0.848778E 00
6	0.487748E-02	0.658452E-02	0.882292E-01	0.969660E 00	0.870904E 00
9	0.105356E-01	0.142305E-01	0.902171E-01	0.977888E 00	0.905565E 00
12	0.176775E-01	0.238933E-01	0.927379E-01	0.988292E 00	0.949581E 00
15	0.256104E-01	0.346411E-01	0.955528E-01	0.999872E 00	0.998812E 00
18	0.335601E-01	0.454268E-01	0.983889E-01	0.101150E 01	0.104850E 01
21	0.407458E-01	0.551890E-01	0.100965E-00	0.102203E 01	0.109370E 01
24	0.464580E-01	0.629579E-01	0.103022E-00	0.103042E 01	0.112983E 01
27	0.501299E-01	0.679558E-01	0.104348E-00	0.103582E 01	0.115314E 01
30	0.513960E-01	0.696798E-01	0.104806E-00	0.103768E 01	0.116120E 01
SLUG FLOW					
0	-0.	-0.	0.915908E-01	0.983543E 00	0.929581E 00
3	0.553040E-03	0.753259E-03	0.917910E-01	0.984356E 00	0.933104E 00
6	0.215695E-02	0.293682E-02	0.923706E-01	0.986714E 00	0.943299E 00
9	0.465195E-02	0.633048E-02	0.932693E-01	0.990378E 00	0.959088E 00
12	0.779037E-02	0.105942E-01	0.943946E-01	0.994978E 00	0.978831E 00
15	0.112623E-01	0.153045E-01	0.956329E-01	0.100036E 01	0.100052E 01
18	0.147268E-01	0.199980E-01	0.968619E-01	0.100511E 01	0.102201E 01
21	0.178460E-01	0.242180E-01	0.979628E-01	0.100966E 01	0.104124E 01
24	0.203172E-01	0.275576E-01	0.988312E-01	0.101325E 01	0.105638E 01
27	0.219018E-01	0.296973E-01	0.993863E-01	0.101555E 01	0.106605E 01
30	0.224475E-01	0.304339E-01	0.995771E-01	0.101634E 01	0.106937E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.892945E-01	0.974032E 00	0.889558E 00
3	0.868402E-03	0.117476E-02	0.896009E-01	0.975297E 00	0.894906E 00
6	0.338940E-02	0.458588E-02	0.904910E-01	0.978970E 00	0.910450E 00
9	0.731832E-02	0.990425E-02	0.918805E-01	0.984698E 00	0.934725E 00
12	0.122731E-01	0.166152E-01	0.936366E-01	0.991928E 00	0.965428E 00
15	0.177709E-01	0.240663E-01	0.955900E-01	0.999958E 00	0.999607E 00
18	0.232741E-01	0.315301E-01	0.975505E-01	0.100800E 01	0.103394E 01
21	0.282434E-01	0.382739E-01	0.993250E-01	0.101528E 01	0.106503E 01
24	0.321903E-01	0.436330E-01	0.100737E-00	0.102106E 01	0.108979E 01
27	0.347258E-01	0.470771E-01	0.101646E-00	0.102477E 01	0.110573E 01
30	0.355997E-01	0.482644E-01	0.101959E-00	0.102605E 01	0.111123E 01
SLUG FLOW					
0	-0.	-0.	0.927420E-01	0.988250E 00	0.949777E 00
3	0.394513E-03	0.536696E-03	0.928842E-01	0.988830E 00	0.952276E 00
6	0.153887E-02	0.209294E-02	0.932961E-01	0.990509E 00	0.959511E 00
9	0.331957E-02	0.451301E-02	0.939355E-01	0.993121E 00	0.970733E 00
12	0.556049E-02	0.755586E-02	0.947374E-01	0.996403E 00	0.984794E 00
15	0.804082E-02	0.109203E-01	0.956215E-01	0.100003E 01	0.100028E 01
18	0.105172E-01	0.142759E-01	0.965007E-01	0.100365E 01	0.101566E 01
21	0.127479E-01	0.172954E-01	0.972895E-01	0.100690E 01	0.102944E 01
24	0.145159E-01	0.196866E-01	0.979127E-01	0.100947E 01	0.104032E 01
27	0.156500E-01	0.212195E-01	0.983116E-01	0.101112E 01	0.104727E 01
30	0.160406E-01	0.217473E-01	0.984488E-01	0.101169E 01	0.104967E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.75$)

TEMPERATURES FOR ORDER

8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.921512E-01	0.985796E 00	0.939494E 00
3	0.475610E-03	0.644534E-03	0.923201E-01	0.986490E 00	0.942449E 00
6	0.185597E-02	0.251524E-02	0.928104E-01	0.988506E 00	0.951028E 00
9	0.400619E-02	0.542953E-02	0.935745E-01	0.991647E 00	0.964397E 00
12	0.671606E-02	0.910275E-02	0.945379E-01	0.995606E 00	0.981255E 00
15	0.972055E-02	0.131759E-01	0.956065E-01	0.999995E 00	0.999958E 00
18	0.127256E-01	0.172503E-01	0.966758E-01	0.100439E 01	0.101868E 01
21	0.154371E-01	0.209271E-01	0.976412E-01	0.100835E 01	0.103558E 01
24	0.175892E-01	0.238457E-01	0.984077E-01	0.101150E 01	0.104900E 01
27	0.189711E-01	0.257200E-01	0.989000E-01	0.101352E 01	0.105762E 01
30	0.194473E-01	0.263659E-01	0.990697E-01	0.101421E 01	0.106059E 01

SLUG FLOW

0	-0.	-0.	0.939500E-01	0.993197E 00	0.970953E 00
3	0.228225E-03	0.310081E-03	0.940318E-01	0.993531E 00	0.972389E 00
6	0.890355E-03	0.120950E-02	0.942691E-01	0.994501E 00	0.976552E 00
9	0.192104E-02	0.260899E-02	0.946379E-01	0.996011E 00	0.983018E 00
12	0.321873E-02	0.437006E-02	0.951013E-01	0.997910E 00	0.991138E 00
15	0.465586E-02	0.631911E-02	0.956132E-01	0.100001E 01	0.100010E 01
18	0.609156E-02	0.826491E-02	0.961233E-01	0.100211E 01	0.100903E 01
21	0.738550E-02	0.100175E-01	0.965819E-01	0.100400E 01	0.101704E 01
24	0.841156E-02	0.114064E-01	0.969448E-01	0.100549E 01	0.102339E 01
27	0.906994E-02	0.122973E-01	0.971774E-01	0.100645E 01	0.102745E 01
30	0.929673E-02	0.126042E-01	0.972574E-01	0.100678E 01	0.102884E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.90$, $b/c=0.50$)

TEMPERATURES FOR ORDER

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ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.954599E-01	0.999390E 00	0.997399E 00
3	0.204421E-04	0.277175E-04	0.954671E-01	0.999420E 00	0.997527E 00
6	0.797664E-04	0.108155E-03	0.954883E-01	0.999506E 00	0.997896E 00
9	0.172163E-03	0.233432E-03	0.955211E-01	0.999641E 00	0.998472E 00
12	0.288586E-03	0.391281E-03	0.955626E-01	0.999811E 00	0.999197E 00
15	0.417635E-03	0.566243E-03	0.956085E-01	0.100000E 01	0.100000E 01
18	0.546678E-03	0.741192E-03	0.956544E-01	0.100019E 01	0.100080E 01
21	0.663084E-03	0.899032E-03	0.956958E-01	0.100036E 01	0.100153E 01
24	0.755460E-03	0.102423E-02	0.957286E-01	0.100049E 01	0.100210E 01
27	0.814768E-03	0.110463E-02	0.957497E-01	0.100058E 01	0.100247E 01
30	0.835204E-03	0.113234E-02	0.957570E-01	0.100061E 01	0.100260E 01

SLUG FLOW

0	-0.	-0.	0.955167E-01	0.999623E 00	0.998394E 00
3	0.126204E-04	0.171133E-04	0.955212E-01	0.999642E 00	0.998473E 00
6	0.492454E-04	0.667757E-04	0.955343E-01	0.999695E 00	0.998701E 00
9	0.106297E-03	0.144121E-03	0.955546E-01	0.999779E 00	0.999057E 00
12	0.178160E-03	0.241570E-03	0.955801E-01	0.999834E 00	0.999504E 00
15	0.257825E-03	0.349580E-03	0.956085E-01	0.100000E 01	0.100000E 01
18	0.337483E-03	0.457574E-03	0.956368E-01	0.100012E 01	0.100050E 01
21	0.409339E-03	0.554985E-03	0.956624E-01	0.100022E 01	0.100094E 01
24	0.466359E-03	0.632282E-03	0.956826E-01	0.100030E 01	0.100130E 01
27	0.502967E-03	0.681906E-03	0.956957E-01	0.100036E 01	0.100153E 01
30	0.515581E-03	0.699094E-03	0.957001E-01	0.100038E 01	0.100163E 01

SUMMARY OF TEMPERATURE CALC. ($k=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.650072E-01	0.852586E 00	0.339945E-00
3	0.474438E-02	0.634306E-02	0.666058E-01	0.858952E 00	0.363608E-00
6	0.186215E-01	0.250060E-01	0.713917E-01	0.877728E 00	0.434964E-00
9	0.405609E-01	0.548574E-01	0.793036E-01	0.907891E 00	0.554698E 00
12	0.687815E-01	0.939012E-01	0.901268E-01	0.947543E 00	0.722062E 00
15	0.100830E-00	0.139142E-00	0.103319E-00	0.993716E 00	0.931180E 00
18	0.133701E-00	0.186534E-00	0.117840E-00	0.104230E 01	0.116694E 01
21	0.164072E-00	0.231194E-00	0.132129E-00	0.108824E 01	0.140359E 01
24	0.188666E-00	0.267948E-00	0.144289E-00	0.112616E 01	0.160795E 01
27	0.204688E-00	0.292163E-00	0.152482E-00	0.115120E 01	0.174692E 01
30	0.210250E-00	0.300619E-00	0.155376E-00	0.115995E 01	0.179621E 01
SLUG FLOW					
0	-0.	-0.	0.848808E-01	0.926225E 00	0.645741E 00
3	0.249909E-02	0.364348E-02	0.860252E-01	0.929963E 00	0.664575E 00
6	0.973459E-02	0.141683E-01	0.893146E-01	0.940759E 00	0.718564E 00
9	0.209542E-01	0.304204E-01	0.943470E-01	0.957421E 00	0.800765E 00
12	0.350069E-01	0.506661E-01	0.100540E-00	0.978163E 00	0.901297E 00
15	0.504772E-01	0.728218E-01	0.107225E-00	0.100084E 01	0.100911E 01
18	0.658382E-01	0.946942E-01	0.113737E-00	0.102319E 01	0.111346E 01
21	0.796047E-01	0.114197E-00	0.119473E-00	0.104310E 01	0.120492E 01
24	0.904702E-01	0.129528E-00	0.123939E-00	0.105872E 01	0.127583E 01
27	0.974190E-01	0.139306E-00	0.126768E-00	0.106868E 01	0.132063E 01
30	0.998085E-01	0.142664E-00	0.127736E-00	0.107210E 01	0.133595E 01

SUMMARY OF TEMPERATURE CALC. ($k=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.92$)

TEMPERATURES FOR ORDER 0

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.768275E-01	0.895953E 00	0.523000E 00
3	0.340867E-02	0.469008E-02	0.781089E-01	0.900706E 00	0.542703E 00
6	0.133451E-01	0.184133E-01	0.818956E-01	0.914628E 00	0.601212E 00
9	0.289527E-01	0.401227E-01	0.879975E-01	0.936693E 00	0.696351E 00
12	0.488476E-01	0.680668E-01	0.960466E-01	0.965160E 00	0.823363E 00
15	0.712001E-01	0.998187E-01	0.105446E-00	0.997589E 00	0.973653E 00
18	0.938680E-01	0.132393E-00	0.115352E-00	0.103094E 01	0.113406E 01
21	0.114588E-00	0.162486E-00	0.124726E-00	0.106182E 01	0.128750E 01
24	0.131215E-00	0.186846E-00	0.132459E-00	0.108686E 01	0.141513E 01
27	0.141976E-00	0.202709E-00	0.137561E-00	0.110319E 01	0.149979E 01
30	0.145699E-00	0.208215E-00	0.139343E-00	0.110886E 01	0.152945E 01
SLUG FLOW					
0	-0.	-0.	0.929451E-01	0.953253E 00	0.776658E 00
3	0.157795E-02	0.228571E-02	0.936528E-01	0.955596E 00	0.788223E 00
6	0.614997E-02	0.889863E-02	0.956937E-01	0.962374E 00	0.821513E 00
9	0.132495E-01	0.191392E-01	0.988347E-01	0.972865E 00	0.872588E 00
12	0.221587E-01	0.319435E-01	0.102730E-00	0.985975E 00	0.935666E 00
15	0.319876E-01	0.460126E-01	0.106970E-00	0.100037E 01	0.100403E 01
18	0.417683E-01	0.599563E-01	0.111133E-00	0.101462E 01	0.107085E 01
21	0.505510E-01	0.724322E-01	0.114826E-00	0.102736E 01	0.112991E 01
24	0.574942E-01	0.822662E-01	0.117717E-00	0.103740E 01	0.117600E 01
27	0.619397E-01	0.885497E-01	0.119555E-00	0.104381E 01	0.120525E 01
30	0.634693E-01	0.907094E-01	0.120145E-00	0.104601E 01	0.121527E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.89$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.857693E-01	0.927695E 00	0.663866E 00
3	0.239308E-02	0.335039E-02	0.867266E-01	0.931106E 00	0.678915E 00
6	0.935486E-02	0.131175E-01	0.895319E-01	0.941053E 00	0.723123E 00
9	0.202478E-01	0.284600E-01	0.939815E-01	0.956692E 00	0.793576E 00
12	0.340598E-01	0.480176E-01	0.997271E-01	0.976651E 00	0.885128E 00
15	0.494823E-01	0.694894E-01	0.106276E-00	0.999103E 00	0.990210E 00
18	0.650221E-01	0.922665E-01	0.113014E-00	0.102190E 01	0.109904E 01
21	0.791410E-01	0.112623E-00	0.119251E-00	0.104275E 01	0.120039E 01
24	0.904133E-01	0.128952E-00	0.124308E-00	0.105950E 01	0.128294E 01
27	0.976819E-01	0.139516E-00	0.127603E-00	0.107034E 01	0.133691E 01
30	0.100192E-00	0.143171E-00	0.128748E-00	0.107410E 01	0.135568E 01

SLUG FLOW					
0	-0.	-0.	0.975446E-01	0.968742E 00	0.851142E 00
3	0.105271E-02	0.151864E-02	0.980105E-01	0.970298E 00	0.858720E 00
6	0.410437E-02	0.591654E-02	0.993568E-01	0.974803E 00	0.880592E 00
9	0.884735E-02	0.127392E-01	0.101436E-00	0.981789E 00	0.914309E 00
12	0.148065E-01	0.212899E-01	0.104028E-00	0.990540E 00	0.956207E 00
15	0.213901E-01	0.307098E-01	0.106864E-00	0.100018E 01	0.100192E 01
18	0.279506E-01	0.400698E-01	0.109664E-00	0.100974E 01	0.104690E 01
21	0.338495E-01	0.484638E-01	0.112159E-00	0.101832E 01	0.108688E 01
24	0.385179E-01	0.550925E-01	0.114119E-00	0.102509E 01	0.111822E 01
27	0.415092E-01	0.595334E-01	0.115369E-00	0.102942E 01	0.113817E 01
30	0.425389E-01	0.607920E-01	0.115798E-00	0.103091E 01	0.114501E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.86$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.921598E-01	0.949958E 00	0.765538E 00
3	0.166565E-02	0.235480E-02	0.928489E-01	0.952361E 00	0.776497E 00
6	0.650570E-02	0.920490E-02	0.948590E-01	0.959351E 00	0.808504E 00
9	0.140624E-01	0.199220E-01	0.980193E-01	0.970292E 00	0.858950E 00
12	0.236158E-01	0.335087E-01	0.102053E-00	0.984170E 00	0.923538E 00
15	0.342466E-01	0.486762E-01	0.106589E-00	0.999674E 00	0.996447E 00
18	0.449199E-01	0.639544E-01	0.111194E-00	0.101530E 01	0.107071E 01
21	0.545848E-01	0.778310E-01	0.115406E-00	0.102951E 01	0.113886E 01
24	0.622792E-01	0.889063E-01	0.118787E-00	0.104085E 01	0.119369E 01
27	0.672307E-01	0.960460E-01	0.120975E-00	0.104817E 01	0.122925E 01
30	0.689389E-01	0.985114E-01	0.121732E-00	0.105069E 01	0.124156E 01

SLUG FLOW					
0	-0.	-0.	0.100404E-00	0.978402E 00	0.897364E 00
3	0.726284E-03	0.104494E-02	0.100722E-00	0.979472E 00	0.902531E 00
6	0.283234E-02	0.407290E-02	0.101644E-00	0.982572E 00	0.917470E 00
9	0.610758E-02	0.877565E-02	0.103072E-00	0.987386E 00	0.940568E 00
12	0.102260E-01	0.146786E-01	0.104856E-00	0.993426E 00	0.969387E 00
15	0.147801E-01	0.211927E-01	0.106816E-00	0.100009E 01	0.100097E 01
18	0.193226E-01	0.276766E-01	0.108758E-00	0.100672E 01	0.103218E 01
21	0.234106E-01	0.335055E-01	0.110494E-00	0.101267E 01	0.106003E 01
24	0.266482E-01	0.381054E-01	0.111861E-00	0.101737E 01	0.108193E 01
27	0.287238E-01	0.410543E-01	0.112734E-00	0.102038E 01	0.109590E 01
30	0.294385E-01	0.420690E-01	0.113034E-00	0.102142E 01	0.110073E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.966217E-01	0.965341E 00	0.836916E 00
3	0.115721E-02	0.164469E-02	0.971092E-01	0.967020E 00	0.844716E 00
6	0.451771E-02	0.642349E-02	0.985275E-01	0.971902E 00	0.867423E 00
9	0.975822E-02	0.138835E-01	0.100747E-00	0.979524E 00	0.903021E 00
12	0.163727E-01	0.233127E-01	0.103562E-00	0.989161E 00	0.948193E 00
15	0.237192E-01	0.338026E-01	0.106705E-00	0.999885E 00	0.998750E 00
18	0.310807E-01	0.443313E-01	0.109872E-00	0.101065E 01	0.104979E 01
21	0.377344E-01	0.538625E-01	0.112750E-00	0.102040E 01	0.109623E 01
24	0.430234E-01	0.614485E-01	0.115047E-00	0.102817E 01	0.113335E 01
27	0.464231E-01	0.663292E-01	0.116528E-00	0.103316E 01	0.115731E 01
30	0.475952E-01	0.680128E-01	0.117039E-00	0.103489E 01	0.116558E 01
SLUG FLOW					
0	-0.	-0.	0.102283E-00	0.984765E 00	0.927707E 00
3	0.511777E-03	0.734997E-03	0.102506E-00	0.985518E 00	0.931319E 00
6	0.199613E-02	0.286569E-02	0.103153E-00	0.987698E 00	0.941775E 00
9	0.430545E-02	0.617742E-02	0.104155E-00	0.991088E 00	0.957973E 00
12	0.721085E-02	0.103386E-01	0.105411E-00	0.995345E 00	0.978236E 00
15	0.104257E-01	0.149360E-01	0.106793E-00	0.100005E 01	0.100051E 01
18	0.136344E-01	0.195175E-01	0.108166E-00	0.100473E 01	0.102259E 01
21	0.165238E-01	0.236371E-01	0.109396E-00	0.100894E 01	0.104234E 01
24	0.188134E-01	0.268975E-01	0.110367E-00	0.101227E 01	0.105791E 01
27	0.202818E-01	0.289867E-01	0.110988E-00	0.101441E 01	0.106786E 01
30	0.207875E-01	0.297058E-01	0.111201E-00	0.101514E 01	0.107127E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.997126E-01	0.975936E 00	0.886509E 00
3	0.804792E-03	0.114707E-02	0.100055E-00	0.977108E 00	0.892003E 00
6	0.314111E-02	0.447791E-02	0.101049E-00	0.980512E 00	0.907972E 00
9	0.678213E-02	0.967142E-02	0.102602E-00	0.985821E 00	0.932913E 00
12	0.113738E-01	0.162253E-01	0.104564E-00	0.992521E 00	0.964461E 00
15	0.164684E-01	0.235027E-01	0.106747E-00	0.999962E 00	0.999585E 00
18	0.215680E-01	0.307931E-01	0.108938E-00	0.100742E 01	0.103487E 01
21	0.261726E-01	0.373808E-01	0.110921E-00	0.101416E 01	0.106683E 01
24	0.298297E-01	0.426161E-01	0.112499E-00	0.101951E 01	0.109226E 01
27	0.321791E-01	0.459808E-01	0.113514E-00	0.102295E 01	0.110867E 01
30	0.329888E-01	0.471408E-01	0.113865E-00	0.102414E 01	0.111432E 01
SLUG FLOW					
0	-0.	-0.	0.103565E-00	0.989115E 00	0.948398E 00
3	0.365405E-03	0.524127E-03	0.103724E-00	0.989651E 00	0.950963E 00
6	0.142538E-02	0.204395E-02	0.104184E-00	0.991206E 00	0.958393E 00
9	0.307492E-02	0.440745E-02	0.104898E-00	0.993624E 00	0.969919E 00
12	0.515105E-02	0.737928E-02	0.105794E-00	0.996665E 00	0.984364E 00
15	0.744930E-02	0.106654E-01	0.106782E-00	0.100003E 01	0.100027E 01
18	0.974427E-02	0.139429E-01	0.107764E-00	0.100338E 01	0.101608E 01
21	0.118118E-01	0.168923E-01	0.108646E-00	0.100639E 01	0.103025E 01
24	0.134507E-01	0.192281E-01	0.109343E-00	0.100878E 01	0.104144E 01
27	0.145020E-01	0.207255E-01	0.109789E-00	0.101031E 01	0.104859E 01
30	0.148641E-01	0.212410E-01	0.109942E-00	0.101083E 01	0.105105E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.75$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.102902E-00	0.986829E 00	0.937780E 00
3	0.441011E-03	0.629878E-03	0.103091E-00	0.987473E 00	0.940819E 00
6	0.172095E-02	0.245806E-02	0.103639E-00	0.989342E 00	0.949640E 00
9	0.371475E-02	0.530615E-02	0.104493E-00	0.992255E 00	0.963386E 00
12	0.622748E-02	0.889601E-02	0.105571E-00	0.995925E 00	0.980721E 00
15	0.901338E-02	0.128768E-01	0.106765E-00	0.999996E 00	0.999954E 00
18	0.117998E-01	0.168590E-01	0.107961E-00	0.100407E 01	0.101920E 01
21	0.143140E-01	0.204526E-01	0.109041E-00	0.100774E 01	0.103659E 01
24	0.163096E-01	0.233052E-01	0.109898E-00	0.101066E 01	0.105039E 01
27	0.175909E-01	0.251372E-01	0.110448E-00	0.101253E 01	0.105925E 01
30	0.180325E-01	0.257685E-01	0.110638E-00	0.101318E 01	0.106231E 01
SLUG FLOW					
0	-0.	-0.	0.104914E-00	0.993692E 00	0.970132E 00
3	0.211566E-03	0.303049E-03	0.105005E-00	0.994002E 00	0.971608E 00
6	0.825381E-03	0.118207E-02	0.105270E-00	0.994922E 00	0.975888E 00
9	0.178090E-02	0.254984E-02	0.105682E-00	0.996301E 00	0.982536E 00
12	0.298404E-02	0.427099E-02	0.106200E-00	0.998061E 00	0.990844E 00
15	0.431657E-02	0.617588E-02	0.106773E-00	0.100031E 01	0.100010E 01
18	0.564787E-02	0.807759E-02	0.107343E-00	0.100195E 01	0.100928E 01
21	0.684782E-02	0.979045E-02	0.107856E-00	0.100370E 01	0.101753E 01
24	0.779940E-02	0.111480E-01	0.108262E-00	0.100509E 01	0.102405E 01
27	0.841002E-02	0.120187E-01	0.108522E-00	0.100598E 01	0.102823E 01
30	0.862037E-02	0.123186E-01	0.108612E-00	0.100629E 01	0.102966E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.889$, $b/c=0.50$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.106602E-00	0.999434E 00	0.997324E 00
3	0.189640E-04	0.271040E-04	0.106610E-00	0.999462E 00	0.997455E 00
6	0.740021E-04	0.105761E-03	0.106633E-00	0.999542E 00	0.997835E 00
9	0.159722E-03	0.228266E-03	0.106670E-00	0.999667E 00	0.998427E 00
12	0.267732E-03	0.382620E-03	0.106716E-00	0.999825E 00	0.999174E 00
15	0.387457E-03	0.553710E-03	0.106768E-00	0.100000E 01	0.100000E 01
18	0.507176E-03	0.724786E-03	0.106819E-00	0.100017E 01	0.100083E 01
21	0.615171E-03	0.879104E-03	0.106865E-00	0.100033E 01	0.100157E 01
24	0.700874E-03	0.100156E-02	0.106902E-00	0.100046E 01	0.100216E 01
27	0.755896E-03	0.108018E-02	0.106926E-00	0.100054E 01	0.100254E 01
30	0.774856E-03	0.110727E-02	0.106934E-00	0.100057E 01	0.100268E 01
SLUG FLOW					
0	-0.	-0.	0.106665E-00	0.999650E 00	0.998348E 00
3	0.117083E-04	0.167345E-04	0.106670E-00	0.999668E 00	0.998429E 00
6	0.456864E-04	0.652979E-04	0.106685E-00	0.999717E 00	0.998664E 00
9	0.986061E-04	0.140931E-03	0.106707E-00	0.999795E 00	0.999029E 00
12	0.165285E-03	0.236224E-03	0.106736E-00	0.999892E 00	0.999490E 00
15	0.239193E-03	0.341842E-03	0.106768E-00	0.100000E 01	0.100000E 01
18	0.313046E-03	0.447447E-03	0.106799E-00	0.100011E 01	0.100051E 01
21	0.379760E-03	0.542701E-03	0.106828E-00	0.100021E 01	0.100097E 01
24	0.432662E-03	0.618287E-03	0.106851E-00	0.100028E 01	0.100134E 01
27	0.466625E-03	0.666812E-03	0.106865E-00	0.100033E 01	0.100157E 01
30	0.478328E-03	0.683532E-03	0.106870E-00	0.100035E 01	0.100165E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.744019E-01	0.867279E 00	0.328917E-00
3	0.427892E-02	0.605918E-02	0.761821E-01	0.873041E 00	0.352580E-00
6	0.167910E-01	0.239086E-01	0.815195E-01	0.890027E 00	0.424171E-00
9	0.365609E-01	0.525222E-01	0.903632E-01	0.917285E 00	0.544950E 00
12	0.619687E-01	0.903530E-01	0.102486E-00	0.953058E 00	0.714736E 00
15	0.907914E-01	0.133671E-00	0.117281E-00	0.994623E 00	0.927865E 00
18	0.120318E-00	0.179491E-00	0.133575E-00	0.103825E 01	0.116890E 01
21	0.147566E-00	0.222769E-00	0.149605E-00	0.107940E 01	0.141129E 01
24	0.169608E-00	0.258448E-00	0.163242E-00	0.111330E 01	0.162079E 01
27	0.183956E-00	0.281981E-00	0.172427E-00	0.113565E 01	0.176332E 01
30	0.188935E-00	0.290204E-00	0.175671E-00	0.114345E 01	0.181388E 01

SLUG FLOW					
0	-0.	-0.	0.967295E-01	0.933868E 00	0.640149E 00
3	0.223485E-02	0.349871E-02	0.979934E-01	0.937194E 00	0.659043E 00
6	0.870859E-02	0.136115E-01	0.101632E-00	0.946811E 00	0.713314E 00
9	0.187566E-01	0.292449E-01	0.107218E-00	0.961684E 00	0.796246E 00
12	0.313582E-01	0.487478E-01	0.114119E-00	0.980246E 00	0.898144E 00
15	0.452511E-01	0.701240E-01	0.121602E-00	0.100060E 01	0.100796E 01
18	0.590659E-01	0.912583E-01	0.128922E-00	0.102072E 01	0.111476E 01
21	0.714632E-01	0.110127E-00	0.135393E-00	0.103869E 01	0.120871E 01
24	0.812586E-01	0.124975E-00	0.140446E-00	0.105282E 01	0.128178E 01
27	0.875279E-01	0.134451E-00	0.143652E-00	0.106184E 01	0.132803E 01
30	0.896846E-01	0.137706E-00	0.144751E-00	0.106494E 01	0.134386E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.92$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.875082E-01	0.906079E 00	0.512584E 00
3	0.308023E-02	0.451857E-02	0.889465E-01	0.910384E 00	0.532585E 00
6	0.120575E-01	0.177481E-01	0.931988E-01	0.922988E 00	0.592051E 00
9	0.261528E-01	0.387001E-01	0.100055E-00	0.942947E 00	0.688947E 00
12	0.441102E-01	0.657079E-01	0.109106E-00	0.968670E 00	0.818608E 00
15	0.642727E-01	0.964437E-01	0.119679E-00	0.997934E 00	0.972552E 00
18	0.847053E-01	0.128022E-00	0.130825E-00	0.102799E 01	0.113671E 01
21	0.103370E-00	0.157232E-00	0.141370E-00	0.105578E 01	0.129409E 01
24	0.118338E-00	0.180900E-00	0.150070E-00	0.107829E 01	0.142510E 01
27	0.128022E-00	0.196322E-00	0.155808E-00	0.109296E 01	0.151202E 01
30	0.131372E-00	0.201676E-00	0.157813E-00	0.109805E 01	0.154248E 01

SLUG FLOW					
0	-0.	-0.	0.105659E-00	0.957914E 00	0.771960E 00
3	0.141855E-02	0.220771E-02	0.106448E-00	0.960014E 00	0.783684E 00
6	0.553002E-02	0.859702E-02	0.108726E-00	0.966092E 00	0.817472E 00
9	0.119181E-01	0.184971E-01	0.112238E-00	0.975513E 00	0.869414E 00
12	0.199407E-01	0.308852E-01	0.116604E-00	0.987303E 00	0.933732E 00
15	0.287995E-01	0.445084E-01	0.121368E-00	0.100027E 01	0.100363E 01
18	0.376226E-01	0.580213E-01	0.126058E-00	0.101314E 01	0.107215E 01
21	0.455522E-01	0.701202E-01	0.130227E-00	0.102466E 01	0.113284E 01
24	0.518251E-01	0.796623E-01	0.133496E-00	0.103374E 01	0.118029E 01
27	0.558434E-01	0.857617E-01	0.135577E-00	0.103955E 01	0.121043E 01
30	0.572264E-01	0.876586E-01	0.136291E-00	0.104154E 01	0.122076E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.89$)

TEMPERATURES FOR ORDER

8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.975028E-01	0.934613E 00	0.655456E 00
3	0.216543E-02	0.324392E-02	0.985813E-01	0.937703E 00	0.670836E 00
6	0.846421E-02	0.127035E-01	0.101742E-00	0.946713E 00	0.716042E 00
9	0.183175E-01	0.275713E-01	0.106757E-00	0.960873E 00	0.788153E 00
12	0.308073E-01	0.465376E-01	0.113233E-00	0.978931E 00	0.881950E 00
15	0.447484E-01	0.678620E-01	0.120616E-00	0.999231E 00	0.989717E 00
18	0.587900E-01	0.894994E-01	0.128212E-00	0.101982E 01	0.110142E 01
21	0.715430E-01	0.109285E-00	0.135244E-00	0.103865E 01	0.120551E 01
24	0.817216E-01	0.125164E-00	0.140945E-00	0.105376E 01	0.129032E 01
27	0.882835E-01	0.135441E-00	0.144660E-00	0.106354E 01	0.134579E 01
30	0.905495E-01	0.138997E-00	0.145951E-00	0.106692E 01	0.136508E 01
SLUG FLOW					
0	-0.	-0.	0.110788E-00	0.971777E 00	0.847504E 00
3	0.949636E-03	0.147222E-02	0.111310E-00	0.973178E 00	0.855236E 00
6	0.370301E-02	0.573640E-02	0.112821E-00	0.977236E 00	0.877567E 00
9	0.798393E-02	0.123536E-01	0.115157E-00	0.983533E 00	0.912028E 00
12	0.133652E-01	0.206501E-01	0.118073E-00	0.991429E 00	0.954915E 00
15	0.193135E-01	0.297939E-01	0.121268E-00	0.100013E 01	0.100178E 01
18	0.252444E-01	0.388835E-01	0.124427E-00	0.100879E 01	0.104797E 01
21	0.305800E-01	0.470381E-01	0.127246E-00	0.101655E 01	0.108908E 01
24	0.348045E-01	0.534797E-01	0.129463E-00	0.102268E 01	0.112133E 01
27	0.375122E-01	0.576017E-01	0.130877E-00	0.102661E 01	0.114188E 01
30	0.384443E-01	0.590196E-01	0.131363E-00	0.102796E 01	0.114893E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.86$)

TEMPERATURES FOR ORDER

8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.104679E-00	0.954687E 00	0.759200E 00
3	0.150872E-02	0.228665E-02	0.105457E-00	0.956865E 00	0.770441E 00
6	0.589248E-02	0.893949E-02	0.107726E-00	0.963200E 00	0.803276E 00
9	0.127360E-01	0.193509E-01	0.111294E-00	0.973113E 00	0.855049E 00
12	0.213862E-01	0.325549E-01	0.115848E-00	0.985684E 00	0.921367E 00
15	0.310100E-01	0.473011E-01	0.120970E-00	0.999720E 00	0.996264E 00
18	0.406704E-01	0.621609E-01	0.126170E-00	0.101386E 01	0.107259E 01
21	0.494162E-01	0.756624E-01	0.130925E-00	0.102671E 01	0.114264E 01
24	0.563779E-01	0.864415E-01	0.134742E-00	0.103697E 01	0.119903E 01
27	0.608573E-01	0.933916E-01	0.137213E-00	0.104359E 01	0.123560E 01
30	0.624026E-01	0.957918E-01	0.138068E-00	0.104587E 01	0.124827E 01
SLUG FLOW					
0	-0.	-0.	0.113992E-00	0.980462E 00	0.894628E 00
3	0.656646E-03	0.101535E-02	0.114351E-00	0.981428E 00	0.899921E 00
6	0.256099E-02	0.395782E-02	0.115389E-00	0.984228E 00	0.915229E 00
9	0.552322E-02	0.852847E-02	0.116997E-00	0.988578E 00	0.938912E 00
12	0.924916E-02	0.142667E-01	0.119009E-00	0.994040E 00	0.968484E 00
15	0.133708E-01	0.206005E-01	0.121222E-00	0.100007E 01	0.100092E 01
18	0.174833E-01	0.269062E-01	0.123415E-00	0.100607E 01	0.103301E 01
21	0.211857E-01	0.325711E-01	0.125377E-00	0.101146E 01	0.106166E 01
24	0.241188E-01	0.370511E-01	0.126924E-00	0.101573E 01	0.108420E 01
27	0.259995E-01	0.399202E-01	0.127913E-00	0.101846E 01	0.109859E 01
30	0.266472E-01	0.409075E-01	0.128252E-00	0.101940E 01	0.110353E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	C.109704E-00	0.968588E 00	0.832297E 00
3	0.104896E-02	0.159990E-02	C.110255E-00	0.970111E 00	0.840313E 00
6	0.409501E-02	0.624888E-02	0.111858E-00	C.974537E 00	0.863651E 00
9	0.884485E-02	C.135373E-01	0.114367E-00	C.981447E 00	0.900224E 00
12	0.148395E-01	0.226833E-01	0.117548E-00	0.990182E 00	0.946689E 00
15	0.214969E-01	0.328935E-01	0.121101E-00	0.999932E 00	0.998685E 00
18	0.281672E-01	0.431438E-01	0.124681E-00	0.100966E 01	C.105118E 01
21	0.341955E-01	0.524246E-01	0.127933E-00	0.101849E 01	0.109896E 01
24	0.389870E-01	0.598125E-01	0.130530E-00	0.102552E 01	0.113716E 01
27	0.420668E-01	0.645662E-01	0.132204E-00	C.103005E 01	0.116182E 01
30	0.431286E-01	0.662061E-01	0.132782E-00	0.103161E 01	0.117033E 01
SLUG FLOW					
0	-0.	-0.	C.116105E-00	0.986201E 00	0.925677E 00
3	0.463388E-03	0.715231E-03	0.116357E-00	C.986881E 00	0.929386E 00
6	0.180750E-02	0.278670E-02	0.117086E-00	0.988855E 00	0.940123E 00
9	0.389894E-02	0.601171E-02	C.118218E-00	0.991922E 00	0.956764E 00
12	0.653075E-02	0.100617E-01	0.119636E-00	0.995777E 00	0.977589E 00
15	0.944353E-02	0.145368E-01	0.121198E-00	0.100004E 01	0.100049E 01
18	0.123515E-01	0.189969E-01	0.122751E-00	0.100428E 01	0.102321E 01
21	0.149707E-01	0.230077E-01	0.124142E-00	0.100810E 01	0.104354E 01
24	0.170465E-01	0.261822E-01	0.125241E-00	0.101112E 01	0.105957E 01
27	0.183780E-01	0.282164E-01	0.125944E-00	0.101336E 01	0.106992E 01
30	0.188366E-01	C.289167E-01	0.126185E-00	0.101373E 01	0.107334E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	C.113192E-00	0.978177E 00	0.883201E 00
3	0.729897E-03	0.111702E-02	0.113579E-00	0.979240E 00	0.888853E 00
6	0.284876E-02	0.436072E-02	C.114704E-00	0.982328E 00	0.905283E 00
9	0.615080E-02	0.941868E-02	0.116460E-00	C.987143E 00	0.930947E 00
12	0.103148E-01	0.156021E-01	0.118679E-00	0.993219E 00	0.963412E 00
15	0.149347E-01	0.226909E-01	0.121148E-00	0.999967E 00	0.999562E 00
18	0.195589E-01	C.299931E-01	0.123626E-00	0.100673E 01	0.103588E 01
21	0.237341E-01	0.364114E-01	0.125869E-00	0.101284E 01	0.106878E 01
24	0.270500E-01	0.415125E-01	0.127654E-00	0.101769E 01	0.109499E 01
27	0.291801E-01	0.447911E-01	0.128803E-00	0.102081E 01	0.111186E 01
30	0.299143E-01	0.459214E-01	0.129199E-00	0.102189E 01	0.111768E 01
SLUG FLOW					
0	-0.	-0.	0.117551E-00	0.990132E 00	0.946901E 00
3	0.331174E-03	0.510498E-03	0.117730E-00	0.990618E 00	0.949539E 00
6	0.129190E-02	0.199083E-02	0.118250E-00	0.992027E 00	0.957179E 00
9	0.278714E-02	0.429297E-02	0.119057E-00	0.994218E 00	0.969034E 00
12	0.466932E-02	0.716775E-02	0.120069E-00	0.996973E 00	0.983895E 00
15	0.675321E-02	C.103888E-01	0.121186E-00	0.100002E 01	0.100027E 01
18	0.883445E-02	0.135816E-01	0.122298E-00	0.100306E 01	0.101654E 01
21	0.107097E-01	0.164549E-01	0.123296E-00	0.100579E 01	0.103113E 01
24	0.121964E-01	0.187305E-01	0.124085E-00	0.100796E 01	0.104265E 01
27	0.131502E-01	0.201893E-01	0.124590E-00	0.100935E 01	0.105007E 01
30	0.134788E-01	0.206916E-01	0.124764E-00	0.100983E 01	0.105256E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.75$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.116796E-00	0.988048E 00	0.935918E 00
3	0.400192E-03	0.613950E-03	0.117010E-00	0.988633E 00	0.939047E 00
6	0.156166E-02	0.239592E-02	0.117631E-00	0.990329E 00	0.948131E 00
9	0.337090E-02	0.517207E-02	0.118598E-00	0.992972E 00	0.962289E 00
12	0.565103E-02	0.867134E-02	0.119817E-00	0.996303E 00	0.980142E 00
15	0.817904E-02	0.125518E-01	0.121167E-00	0.999996E 00	0.999951E 00
18	0.107075E-01	0.164337E-01	0.122523E-00	0.100369E 01	0.101978E 01
21	0.129889E-01	0.199369E-01	0.123744E-00	0.100703E 01	0.103768E 01
24	0.147497E-01	0.227179E-01	0.124715E-00	0.100967E 01	0.105190E 01
27	0.159625E-01	0.245038E-01	0.125338E-00	0.101137E 01	0.106103E 01
30	0.163631E-01	0.251192E-01	0.125553E-00	0.101196E 01	0.106418E 01
SLUG FLOW					
0	-0.	-0.	0.119073E-00	0.994277E 00	0.969240E 00
3	0.191923E-03	0.295411E-03	0.119177E-00	0.994558E 00	0.970766E 00
6	0.748764E-03	0.115228E-02	0.119477E-00	0.995374E 00	0.975166E 00
9	0.161565E-02	0.248558E-02	0.119943E-00	0.996643E 00	0.982011E 00
12	0.270725E-02	0.416336E-02	0.120530E-00	0.998240E 00	0.990609E 00
15	0.391636E-02	0.602026E-02	0.121177E-00	0.100001E 01	0.100010E 01
18	0.512448E-02	0.787406E-02	0.121823E-00	0.100177E 01	0.100956E 01
21	0.621349E-02	0.954377E-02	0.122404E-00	0.100336E 01	0.101805E 01
24	0.707716E-02	0.108671E-01	0.122863E-00	0.100462E 01	0.102477E 01
27	0.763141E-02	0.117159E-01	0.123158E-00	0.100543E 01	0.102908E 01
30	0.782234E-02	0.120062E-01	0.123259E-00	0.100571E 01	0.103056E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.875$, $b/c=0.50$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.120984E-00	0.999486E 00	0.997242E 00
3	0.172189E-04	0.264366E-04	0.120993E-00	0.999511E 00	0.997377E 00
6	0.671896E-04	0.103157E-03	0.121020E-00	0.999584E 00	0.997769E 00
9	0.145019E-03	0.222645E-03	0.121061E-00	0.999698E 00	0.998379E 00
12	0.243086E-03	0.373199E-03	0.121114E-00	0.999841E 00	0.999148E 00
15	0.351790E-03	0.540075E-03	0.121172E-00	0.100000E 01	0.100000E 01
18	0.460490E-03	0.706938E-03	0.121230E-00	0.100016E 01	0.100085E 01
21	0.558545E-03	0.857455E-03	0.121283E-00	0.100030E 01	0.100162E 01
24	0.636360E-03	0.976898E-03	0.121324E-00	0.100042E 01	0.100223E 01
27	0.686319E-03	0.105358E-02	0.121351E-00	0.100049E 01	0.100262E 01
30	0.703533E-03	0.108000E-02	0.121360E-00	0.100051E 01	0.100276E 01
SLUG FLOW					
0	-0.	-0.	0.121056E-00	0.999683E 00	0.998297E 00
3	0.106304E-04	0.163225E-04	0.121061E-00	0.999698E 00	0.998381E 00
6	0.414803E-04	0.636902E-04	0.121078E-00	0.999743E 00	0.998623E 00
9	0.895202E-04	0.137461E-03	0.121104E-00	0.999813E 00	0.999000E 00
12	0.150069E-03	0.230407E-03	0.121136E-00	0.999902E 00	0.999474E 00
15	0.217174E-03	0.333425E-03	0.121172E-00	0.100000E 01	0.100000E 01
18	0.284275E-03	0.436429E-03	0.121208E-00	0.100010E 01	0.100053E 01
21	0.344803E-03	0.529337E-03	0.121240E-00	0.100019E 01	0.100100E 01
24	0.392836E-03	0.603061E-03	0.121266E-00	0.100026E 01	0.100136E 01
27	0.423674E-03	0.650391E-03	0.121282E-00	0.100030E 01	0.100162E 01
30	0.434299E-03	0.666699E-03	0.121288E-00	0.100032E 01	0.100170E 01

SUMMARY OF TEMPERATURE CALC. ($k=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.870335E-01	0.883915E 00	0.317519E-00
3	0.375297E-02	0.576566E-02	0.890462E-01	0.888999E 00	0.341192E-00
6	0.147215E-01	0.227744E-01	0.950863E-01	0.903971E 00	0.413057E-00
9	0.320355E-01	0.501102E-01	0.105108E-00	0.927950E 00	0.534952E 00
12	0.542559E-01	0.860818E-01	0.118859E-00	0.959329E 00	0.707269E 00
15	0.794202E-01	0.128031E-00	0.135644E-00	0.995662E 00	0.924543E 00
18	0.105152E-00	0.172236E-00	0.154118E-00	0.103365E 01	0.117099E 01
21	0.128857E-00	0.214099E-00	0.172276E-00	0.106938E 01	0.141922E 01
24	0.148604E-00	0.248679E-00	0.187708E-00	0.109871E 01	0.163396E 01
27	0.160455E-00	0.271517E-00	0.198095E-00	0.111801E 01	0.178009E 01
30	0.164773E-00	0.279501E-00	0.201761E-00	0.112475E 01	0.183193E 01
SLUG FLOW					
0	-0.	-0.	0.112439E-00	0.942462E 00	0.634438E 00
3	0.193996E-02	0.335093E-02	0.113850E-00	0.945336E 00	0.653388E 00
6	0.756229E-02	0.130429E-01	0.117919E-00	0.953653E 00	0.707932E 00
9	0.162968E-01	0.280435E-01	0.124185E-00	0.966539E 00	0.791593E 00
12	0.272645E-01	0.467857E-01	0.131900E-00	0.982662E 00	0.894875E 00
15	0.393729E-01	0.673618E-01	0.140427E-00	0.100039E 01	0.100675E 01
18	0.514303E-01	0.877369E-01	0.148745E-00	0.101797E 01	0.111605E 01
21	0.622645E-01	0.105952E-00	0.156127E-00	0.103370E 01	0.121260E 01
24	0.708341E-01	0.120301E-00	0.161906E-00	0.104611E 01	0.128791E 01
27	0.763229E-01	0.129465E-00	0.165581E-00	0.105403E 01	0.133567E 01
30	0.732118E-01	0.132614E-00	0.166841E-00	0.105676E 01	0.135203E 01

SUMMARY OF TEMPERATURE CALC. ($k=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.92$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.101746E-00	0.917666E 00	0.501776E 00
3	0.270459E-02	0.434048E-02	0.103382E-00	0.921459E 00	0.522091E 00
6	0.105845E-01	0.170575E-01	0.108219E-00	0.932557E 00	0.582563E 00
9	0.229494E-01	0.372237E-01	0.116021E-00	0.950110E 00	0.681299E 00
12	0.386892E-01	0.632614E-01	0.126319E-00	0.972692E 00	0.813717E 00
15	0.563443E-01	0.929452E-01	0.138347E-00	0.998331E 00	0.971042E 00
18	0.742176E-01	0.123493E-00	0.151022E-00	0.102461E 01	0.113948E 01
21	0.905285E-01	0.151791E-00	0.163009E-00	0.104886E 01	0.130093E 01
24	0.103599E-00	0.174745E-00	0.172893E-00	0.106847E 01	0.143539E 01
27	0.112050E-00	0.189713E-00	0.179410E-00	0.108124E 01	0.152464E 01
30	0.114972E-00	0.194912E-00	0.181686E-00	0.108567E 01	0.155592E 01
SLUG FLOW					
0	-0.	-0.	0.122432E-00	0.963223E 00	0.767116E 00
3	0.123784E-02	0.212735E-02	0.123322E-00	0.965050E 00	0.779002E 00
6	0.482663E-02	0.828621E-02	0.125892E-00	0.970341E 00	0.813296E 00
9	0.104058E-01	0.178352E-01	0.129862E-00	0.978552E 00	0.866126E 00
12	0.174178E-01	0.297936E-01	0.134808E-00	0.988844E 00	0.931718E 00
15	0.251674E-01	0.429559E-01	0.140221E-00	0.100019E 01	0.100321E 01
18	0.328928E-01	0.560226E-01	0.145562E-00	0.101146E 01	0.107347E 01
21	0.398414E-01	0.677308E-01	0.150322E-00	0.102156E 01	0.113586E 01
24	0.453422E-01	0.769702E-01	0.154066E-00	0.102954E 01	0.118472E 01
27	0.488676E-01	0.828784E-01	0.156443E-00	0.103465E 01	0.121580E 01
30	0.500812E-01	0.849099E-01	0.157261E-00	0.103641E 01	0.122646E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.89$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.113050E-00	0.942585E 00	0.646702E 00
3	0.190311E-02	0.313302E-02	0.114280E-00	0.945306E 00	0.662429E 00
6	0.743786E-02	0.122724E-01	0.117884E-00	0.953237E 00	0.708682E 00
9	0.160930E-01	0.266460E-01	0.123603E-00	0.965691E 00	0.782520E 00
12	0.270590E-01	0.449970E-01	0.130988E-00	0.981560E 00	0.878660E 00
15	0.392926E-01	0.656484E-01	0.139406E-00	0.999378E 00	0.989219E 00
18	0.516074E-01	0.866212E-01	0.148064E-00	0.101743E 01	0.110390E 01
21	0.627862E-01	0.105814E-00	0.156077E-00	0.103392E 01	0.121083E 01
24	0.717044E-01	0.121226E-00	0.162572E-00	0.104715E 01	0.129799E 01
27	0.774520E-01	0.131206E-00	0.166804E-00	0.105570E 01	0.135500E 01
30	0.794363E-01	0.134660E-00	0.168273E-00	0.105866E 01	0.137483E 01
SLUG FLOW					
0	-0.	-0.	0.128213E-00	0.975265E 00	0.843729E 00
3	0.831533E-03	0.142411E-02	0.128805E-00	0.976489E 00	0.851620E 00
6	0.324294E-02	0.554964E-02	0.130520E-00	0.980036E 00	0.874424E 00
9	0.699351E-02	0.119537E-01	0.133173E-00	0.985546E 00	0.909655E 00
12	0.117104E-01	0.199863E-01	0.136489E-00	0.992462E 00	0.953566E 00
15	0.169272E-01	0.288434E-01	0.140129E-00	0.100009E 01	0.100163E 01
18	0.221318E-01	0.376518E-01	0.143733E-00	0.100769E 01	0.104907E 01
21	0.268165E-01	0.455573E-01	0.146954E-00	0.101451E 01	0.109135E 01
24	0.305272E-01	0.518040E-01	0.149490E-00	0.101991E 01	0.112457E 01
27	0.329064E-01	0.558022E-01	0.151109E-00	0.102336E 01	0.114574E 01
30	0.337256E-01	0.571776E-01	0.151665E-00	0.102455E 01	0.115301E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.86$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.121201E-00	0.960164E 00	0.752586E 00
3	0.132701E-02	0.221550E-02	0.122090E-00	0.962081E 00	0.764121E 00
6	0.518241E-02	0.866243E-02	0.124681E-00	0.967657E 00	0.797824E 00
9	0.112600E-01	0.187548E-01	0.128756E-00	0.976380E 00	0.850984E 00
12	0.188044E-01	0.315595E-01	0.133956E-00	0.987436E 00	0.919108E 00
15	0.272622E-01	0.458663E-01	0.139805E-00	0.999774E 00	0.996080E 00
18	0.357496E-01	0.602901E-01	0.145742E-00	0.101220E 01	0.107455E 01
21	0.434314E-01	0.734007E-01	0.151171E-00	0.102348E 01	0.114660E 01
24	0.495446E-01	0.838711E-01	0.155528E-00	0.103248E 01	0.120460E 01
27	0.534774E-01	0.906238E-01	0.158348E-00	0.103828E 01	0.124222E 01
30	0.548340E-01	0.929561E-01	0.159323E-00	0.104029E 01	0.125525E 01
SLUG FLOW					
0	-0.	-0.	0.131843E-00	0.982842E 00	0.891779E 00
3	0.576297E-03	0.984562E-03	0.132251E-00	0.983689E 00	0.897203E 00
6	0.224783E-02	0.383803E-02	0.133433E-00	0.986144E 00	0.912893E 00
9	0.484851E-02	0.827113E-02	0.135265E-00	0.989960E 00	0.937183E 00
12	0.812074E-02	0.138378E-01	0.137560E-00	0.994754E 00	0.967539E 00
15	0.117418E-01	0.199835E-01	0.140084E-00	0.100005E 01	0.100087E 01
18	0.153563E-01	0.261035E-01	0.142590E-00	0.100533E 01	0.103386E 01
21	0.186114E-01	0.316025E-01	0.144834E-00	0.101007E 01	0.106335E 01
24	0.211909E-01	0.359520E-01	0.146604E-00	0.101382E 01	0.108657E 01
27	0.228453E-01	0.387378E-01	0.147735E-00	0.101623E 01	0.110139E 01
30	0.234151E-01	0.396966E-01	0.148124E-00	0.101706E 01	0.110649E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP.	OUTSIDE WALL SURFACE TEMP.	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.126925E-00	0.972360E 00	0.827468E 00
3	0.923208E-03	0.155306E-02	0.127555E-00	0.973701E 00	0.835710E 00
6	0.360397E-02	0.606632E-02	0.129388E-00	0.977599E 00	0.859708E 00
9	0.778381E-02	0.131139E-01	0.132255E-00	0.983682E 00	0.897322E 00
12	0.130584E-01	0.220252E-01	0.135892E-00	0.991369E 00	0.945120E 00
15	0.189153E-01	0.319433E-01	0.139953E-00	0.999920E 00	0.998618E 00
18	0.247827E-01	0.419026E-01	0.144045E-00	0.100850E 01	0.105264E 01
21	0.300646E-01	0.509219E-01	0.147763E-00	0.101627E 01	0.110182E 01
24	0.342982E-01	0.581028E-01	0.150730E-00	0.102245E 01	0.114115E 01
27	0.370663E-01	0.627239E-01	0.152643E-00	0.102643E 01	0.116653E 01
30	0.379399E-01	0.643181E-01	0.153304E-00	0.102780E 01	0.117530E 01

SLUG FLOW					
0	-0.	-0.	0.134245E-00	0.987866E 00	0.923557E 00
3	0.407301E-03	0.694603E-03	0.134533E-00	0.988464E 00	0.927368E 00
6	0.158882E-02	0.270835E-02	0.135365E-00	0.990197E 00	0.938398E 00
9	0.342756E-02	0.583873E-02	0.136657E-00	0.992892E 00	0.955500E 00
12	0.574188E-02	0.977273E-02	0.138276E-00	0.996281E 00	0.976912E 00
15	0.830390E-02	0.141200E-01	0.140062E-00	0.100003E 01	0.100047E 01
18	0.108623E-01	0.184532E-01	0.141836E-00	0.100376E 01	0.102385E 01
21	0.131673E-01	0.223502E-01	0.143428E-00	0.100712E 01	0.104479E 01
24	0.149945E-01	0.254349E-01	0.144686E-00	0.100979E 01	0.106131E 01
27	0.161666E-01	0.274116E-01	0.145490E-00	0.101149E 01	0.107187E 01
30	0.165703E-01	0.280921E-01	0.145767E-00	0.101208E 01	0.107549E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP.	OUTSIDE WALL SURFACE TEMP.	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.130906E-00	0.980786E 00	0.879738E 00
3	0.642711E-03	0.108556E-02	0.131349E-00	0.981722E 00	0.885556E 00
6	0.250843E-02	0.423803E-02	0.132635E-00	0.984442E 00	0.902469E 00
9	0.541585E-02	0.915412E-02	0.134644E-00	0.988682E 00	0.928889E 00
12	0.908198E-02	0.153591E-01	0.137183E-00	0.994033E 00	0.962314E 00
15	0.131493E-01	0.222506E-01	0.140007E-00	0.999973E 00	0.999538E 00
18	0.172200E-01	0.291559E-01	0.142841E-00	0.100592E 01	0.103694E 01
21	0.208953E-01	0.353968E-01	0.145407E-00	0.101130E 01	0.107083E 01
24	0.238140E-01	0.403575E-01	0.147449E-00	0.101557E 01	0.109782E 01
27	0.256888E-01	0.435460E-01	0.148763E-00	0.101832E 01	0.111519E 01
30	0.263350E-01	0.446453E-01	0.149216E-00	0.101927E 01	0.112119E 01

SLUG FLOW					
0	-0.	-0.	0.135893E-00	0.991315E 00	0.945336E 00
3	0.291380E-03	0.496249E-03	0.136098E-00	0.991742E 00	0.948050E 00
6	0.113671E-02	0.193528E-02	0.136692E-00	0.992981E 00	0.955910E 00
9	0.245251E-02	0.417325E-02	0.137614E-00	0.994909E 00	0.968109E 00
12	0.410904E-02	0.698745E-02	0.138772E-00	0.997333E 00	0.983405E 00
15	0.594342E-02	0.100995E-01	0.140049E-00	0.100602E 01	0.100026E 01
18	0.777582E-02	0.132036E-01	0.141321E-00	0.100269E 01	0.101702E 01
21	0.942714E-02	0.159973E-01	0.142463E-00	0.100510E 01	0.103205E 01
24	0.107365E-01	0.182098E-01	0.143367E-00	0.100701E 01	0.104393E 01
27	0.115766E-01	0.196282E-01	0.143945E-00	0.100823E 01	0.105152E 01
30	0.118660E-01	0.201166E-01	0.144144E-00	0.100865E 01	0.105414E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.75$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.135025E-00	0.989471E 00	0.933967E 00
3	0.352575E-03	0.597257E-03	0.135270E-00	0.989986E 00	0.937191E 00
6	0.137585E-02	0.233080E-02	0.135980E-00	0.991480E 00	0.946551E 00
9	0.296980E-02	0.503155E-02	0.137087E-00	0.993838E 00	0.961138E 00
12	0.497859E-02	0.843588E-02	0.138483E-00	0.996743E 00	0.979534E 00
15	0.720574E-02	0.122111E-01	0.140031E-00	0.999977E 00	0.999947E 00
18	0.943328E-02	0.159880E-01	0.141580E-00	0.100325E 01	0.102038E 01
21	0.114431E-01	0.193965E-01	0.142979E-00	0.100619E 01	0.103883E 01
24	0.130384E-01	0.221023E-01	0.144009E-00	0.100852E 01	0.105348E 01
27	0.140627E-01	0.238400E-01	0.144803E-00	0.101002E 01	0.106289E 01
30	0.144157E-01	0.244389E-01	0.145049E-00	0.101054E 01	0.106614E 01
SLUG FLOW					
0	-0.	-0.	0.137632E-00	0.994959E 00	0.968306E 00
3	0.169024E-03	0.287412E-03	0.137751E-00	0.995207E 00	0.969872E 00
6	0.659444E-03	0.112108E-02	0.138094E-00	0.995925E 00	0.974410E 00
9	0.142297E-02	0.241827E-02	0.138628E-00	0.997042E 00	0.981462E 00
12	0.238451E-02	0.405062E-02	0.139298E-00	0.998449E 00	0.990319E 00
15	0.344966E-02	0.585722E-02	0.140040E-00	0.100001E 01	0.100010E 01
18	0.451405E-02	0.766081E-02	0.140779E-00	0.100156E 01	0.100984E 01
21	0.547360E-02	0.926529E-02	0.141444E-00	0.100296E 01	0.101860E 01
24	0.623466E-02	0.105728E-01	0.141770E-00	0.100407E 01	0.102553E 01
27	0.672309E-02	0.113986E-01	0.142308E-00	0.100478E 01	0.102996E 01
30	0.689136E-02	0.116830E-01	0.142424E-00	0.100503E 01	0.103149E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.857$, $b/c=0.50$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.139818E-00	0.999547E 00	0.997156E 00
3	0.151707E-04	0.257364E-04	0.139829E-00	0.999569E 00	0.997296E 00
6	0.592283E-04	0.100424E-03	0.139859E-00	0.999633E 00	0.997700E 00
9	0.127836E-03	0.216748E-03	0.139907E-00	0.999734E 00	0.998329E 00
12	0.214284E-03	0.363313E-03	0.139967E-00	0.999860E 00	0.999122E 00
15	0.310109E-03	0.525769E-03	0.140034E-00	0.100000E 01	0.100000E 01
18	0.405930E-03	0.688212E-03	0.140101E-00	0.100014E 01	0.100088E 01
21	0.492368E-03	0.834741E-03	0.140161E-00	0.100027E 01	0.100167E 01
24	0.560965E-03	0.951019E-03	0.140208E-00	0.100037E 01	0.100230E 01
27	0.605005E-03	0.102567E-02	0.140239E-00	0.100043E 01	0.100270E 01
30	0.620180E-03	0.105139E-02	0.140249E-00	0.100045E 01	0.100284E 01
SLUG FLOW					
0	-0.	-0.	0.139901E-00	0.999720E 00	0.998244E 00
3	0.937068E-05	0.158902E-04	0.139907E-00	0.999734E 00	0.998330E 00
6	0.365649E-04	0.620034E-04	0.139926E-00	0.999774E 00	0.998580E 00
9	0.789195E-04	0.133820E-03	0.139956E-00	0.999836E 00	0.998969E 00
12	0.132287E-03	0.224305E-03	0.139993E-00	0.999914E 00	0.999458E 00
15	0.191441E-03	0.324593E-03	0.140034E-00	0.100000E 01	0.100000E 01
18	0.250592E-03	0.424868E-03	0.140075E-00	0.100009E 01	0.100054E 01
21	0.303950E-03	0.515315E-03	0.140112E-00	0.100016E 01	0.100103E 01
24	0.346293E-03	0.587086E-03	0.140142E-00	0.100023E 01	0.100142E 01
27	0.373478E-03	0.633162E-03	0.140160E-00	0.100027E 01	0.100167E 01
30	0.382845E-03	0.649038E-03	0.140167E-00	0.100028E 01	0.100175E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.104931E-00	0.902880E 00	0.306089E-00
3	0.315288E-02	0.547108E-02	0.107249E-00	0.907190E 00	0.329787E-00
6	0.123603E-01	0.210369E-01	0.114207E-00	0.919862E 00	0.401964E-00
9	0.268721E-01	0.476933E-01	0.125752E-00	0.940092E 00	0.525029E 00
12	0.454570E-01	0.821069E-01	0.141581E-00	0.966449E 00	0.699920E 00
15	0.664516E-01	0.122392E-00	0.160871E-00	0.996809E 00	0.921346E 00
18	0.878635E-01	0.164994E-00	0.182061E-00	0.102839E 01	0.117316E 01
21	0.107540E-00	0.205454E-00	0.202844E-00	0.105794E 01	0.142716E 01
24	0.123401E-00	0.238947E-00	0.220476E-00	0.108211E 01	0.164702E 01
27	0.133699E-00	0.261098E-00	0.232329E-00	0.109797E 01	0.179668E 01
30	0.137268E-00	0.268847E-00	0.236510E-00	0.110349E 01	0.184978E 01
SLUG FLOW					
0	-0.	-0.	0.134265E-00	0.952171E 00	0.628783E 00
3	0.160926E-02	0.320468E-02	0.135861E-00	0.954544E 00	0.647784E 00
6	0.627521E-02	0.124800E-01	0.140470E-00	0.961420E 00	0.702586E 00
9	0.135300E-01	0.268533E-01	0.147589E-00	0.972091E 00	0.786953E 00
12	0.226497E-01	0.448403E-01	0.156456E-00	0.985473E 00	0.891596E 00
15	0.327308E-01	0.646210E-01	0.166156E-00	0.100022E 01	0.100551E 01
18	0.427826E-01	0.842401E-01	0.175723E-00	0.101489E 01	0.111732E 01
21	0.518255E-01	0.101804E-00	0.184244E-00	0.102805E 01	0.121646E 01
24	0.589853E-01	0.115654E-00	0.190934E-00	0.103844E 01	0.129401E 01
27	0.635745E-01	0.124506E-00	0.195197E-00	0.104509E 01	0.134330E 01
30	0.651544E-01	0.127549E-00	0.196659E-00	0.104738E 01	0.136019E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.92$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.121696E-00	0.931005E 00	0.490903E-00
3	0.227173E-02	0.416114E-02	0.123585E-00	0.934207E 00	0.511540E 00
6	0.888741E-02	0.163624E-01	0.129171E-00	0.943567E 00	0.573042E 00
9	0.192593E-01	0.357384E-01	0.138175E-00	0.958342E 00	0.673648E 00
12	0.324460E-01	0.608016E-01	0.150051E-00	0.977304E 00	0.808853E 00
15	0.472165E-01	0.894305E-01	0.163910E-00	0.998771E 00	0.969777E 00
18	0.621478E-01	0.118948E-00	0.178495E-00	0.102071E 01	0.114229E 01
21	0.757551E-01	0.146333E-00	0.192274E-00	0.104090E 01	0.130779E 01
24	0.866467E-01	0.168575E-00	0.203624E-00	0.105719E 01	0.144569E 01
27	0.936827E-01	0.183090E-00	0.211102E-00	0.106778E 01	0.153725E 01
30	0.961150E-01	0.188133E-00	0.213714E-00	0.107145E 01	0.156933E 01
SLUG FLOW					
0	-0.	-0.	0.145590E-00	0.969298E 00	0.762276E 00
3	0.103196E-02	0.204712E-02	0.146605E-00	0.970817E 00	0.774322E 00
6	0.402469E-02	0.797579E-02	0.149541E-00	0.975219E 00	0.809117E 00
9	0.867967E-02	0.171738E-01	0.154084E-00	0.982056E 00	0.862827E 00
12	0.145344E-01	0.287024E-01	0.159758E-00	0.990639E 00	0.929688E 00
15	0.210103E-01	0.414031E-01	0.165983E-00	0.100011E 01	0.100277E 01
18	0.274715E-01	0.540226E-01	0.172142E-00	0.100954E 01	0.107479E 01
21	0.332876E-01	0.653387E-01	0.177641E-00	0.101801E 01	0.113888E 01
24	0.378949E-01	0.742739E-01	0.181969E-00	0.102471E 01	0.118917E 01
27	0.408491E-01	0.799898E-01	0.184731E-00	0.102900E 01	0.122120E 01
30	0.418663E-01	0.819556E-01	0.185680E-00	0.103048E 01	0.123219E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.89$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.134655E-00	0.951823E 00	0.637870E 00
3	0.159893E-02	0.302104E-02	0.136077E-00	0.954115E 00	0.653951E 00
6	0.624783E-02	0.118371E-01	0.140244E-00	0.960793E 00	0.701265E 00
9	0.135142E-01	0.257121E-01	0.146853E-00	0.971269E 00	0.776855E 00
12	0.227144E-01	0.434429E-01	0.155383E-00	0.984598E 00	0.875362E 00
15	0.329702E-01	0.634162E-01	0.165101E-00	0.999541E 00	0.988736E 00
18	0.432860E-01	0.837203E-01	0.175089E-00	0.101466E 01	0.110642E 01
21	0.526432E-01	0.102316E-00	0.184328E-00	0.102845E 01	0.121620E 01
24	0.601034E-01	0.117261E-00	0.191812E-00	0.103949E 01	0.130570E 01
27	0.649092E-01	0.126941E-00	0.196687E-00	0.104663E 01	0.136426E 01
30	0.665681E-01	0.130292E-00	0.198379E-00	0.104909E 01	0.138463E 01
SLUG FLOW					
0	-0.	-0.	0.152186E-00	0.979291E 00	0.839935E 00
3	0.695554E-03	0.137578E-02	0.152866E-00	0.980313E 00	0.847985E 00
6	0.271300E-02	0.536203E-02	0.154835E-00	0.983276E 00	0.871267E 00
9	0.585191E-02	0.115519E-01	0.157886E-00	0.987882E 00	0.907264E 00
12	0.980140E-02	0.193191E-01	0.161704E-00	0.993668E 00	0.952202E 00
15	0.141720E-01	0.278876E-01	0.165902E-00	0.100006E 01	0.100147E 01
18	0.185347E-01	0.364128E-01	0.170064E-00	0.100643E 01	0.105018E 01
21	0.224637E-01	0.440671E-01	0.173789E-00	0.101216E 01	0.109365E 01
24	0.255773E-01	0.501173E-01	0.176726E-00	0.101669E 01	0.112783E 01
27	0.275742E-01	0.539905E-01	0.178602E-00	0.101959E 01	0.114963E 01
30	0.282619E-01	0.553231E-01	0.179247E-00	0.102059E 01	0.115712E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.86$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.144035E-00	0.966539E 00	0.745898E 00
3	0.111540E-02	0.214351E-02	0.145063E-00	0.968152E 00	0.757732E 00
6	0.435555E-02	0.836214E-02	0.148061E-00	0.972845E 00	0.792314E 00
9	0.941153E-02	0.181518E-01	0.152775E-00	0.980181E 00	0.846879E 00
12	0.157985E-01	0.305529E-01	0.158789E-00	0.989472E 00	0.916831E 00
15	0.228994E-01	0.444158E-01	0.165551E-00	0.999833E 00	0.995900E 00
18	0.300222E-01	0.583991E-01	0.172412E-00	0.101026E 01	0.107654E 01
21	0.364663E-01	0.711151E-01	0.178684E-00	0.101972E 01	0.115059E 01
24	0.415929E-01	0.812741E-01	0.183716E-00	0.102726E 01	0.121022E 01
27	0.448902E-01	0.878277E-01	0.186972E-00	0.103212E 01	0.124890E 01
30	0.460274E-01	0.900914E-01	0.188099E-00	0.103380E 01	0.126230E 01
SLUG FLOW					
0	-0.	-0.	0.156349E-00	0.985607E 00	0.888905E 00
3	0.483138E-03	0.953510E-03	0.156819E-00	0.986316E 00	0.894462E 00
6	0.188464E-02	0.371722E-02	0.158181E-00	0.988372E 00	0.910535E 00
9	0.406570E-02	0.801153E-02	0.160295E-00	0.991570E 00	0.935436E 00
12	0.681084E-02	0.134050E-01	0.162943E-00	0.995589E 00	0.966582E 00
15	0.984974E-02	0.193609E-01	0.165860E-00	0.100003E 01	0.100081E 01
18	0.128843E-01	0.252931E-01	0.168758E-00	0.100446E 01	0.103473E 01
21	0.156182E-01	0.306244E-01	0.171355E-00	0.100845E 01	0.106506E 01
24	0.177853E-01	0.348419E-01	0.173405E-00	0.101161E 01	0.108897E 01
27	0.191756E-01	0.375435E-01	0.174717E-00	0.101363E 01	0.110423E 01
30	0.196544E-01	0.384732E-01	0.175168E-00	0.101433E 01	0.110948E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.150638E-00	0.976765E 00	0.822577E 00
3	0.776344E-03	0.150559E-02	0.151367E-00	0.977894E 00	0.831048E 00
6	0.303049E-02	0.588133E-02	0.153489E-00	0.981173E 00	0.855716E 00
9	0.654470E-02	0.127153E-01	0.156809E-00	0.986290E 00	0.894385E 00
12	0.109785E-01	0.213546E-01	0.161018E-00	0.992754E 00	0.943533E 00
15	0.159009E-01	0.309809E-01	0.165718E-00	0.999941E 00	0.998552E 00
18	0.208309E-01	0.406456E-01	0.170453E-00	0.100715E 01	0.105412E 01
21	0.252849E-01	0.494001E-01	0.174753E-00	0.101367E 01	0.110472E 01
24	0.288241E-01	0.563716E-01	0.178186E-00	0.101886E 01	0.114518E 01
27	0.310984E-01	0.608586E-01	0.180398E-00	0.102220E 01	0.117129E 01
30	0.318824E-01	0.624067E-01	0.181162E-00	0.102335E 01	0.118032E 01
SLUG FLOW					
0	-0.	-0.	0.159114E-00	0.989808E 00	0.921413E 00
3	0.341972E-03	0.673743E-03	0.159446E-00	0.990309E 00	0.925325E 00
6	0.133407E-02	0.262709E-02	0.160407E-00	0.991764E 00	0.936652E 00
9	0.287827E-02	0.566377E-02	0.161900E-00	0.994026E 00	0.954219E 00
12	0.482231E-02	0.946036E-02	0.163772E-00	0.996871E 00	0.976226E 00
15	0.697500E-02	0.136983E-01	0.165838E-00	0.100002E 01	0.100045E 01
18	0.912526E-02	0.179030E-01	0.167892E-00	0.100316E 01	0.102451E 01
21	0.110630E-01	0.216847E-01	0.169736E-00	0.100599E 01	0.104606E 01
24	0.125994E-01	0.246783E-01	0.171193E-00	0.100822E 01	0.106307E 01
27	0.135851E-01	0.265968E-01	0.172126E-00	0.100966E 01	0.107394E 01
30	0.139247E-01	0.272572E-01	0.172447E-00	0.101016E 01	0.107768E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.155237E-00	0.983839E 00	0.876225E 00
3	0.540680E-03	0.105365E-02	0.155750E-00	0.984627E 00	0.882212E 00
6	0.211017E-02	0.411359E-02	0.157241E-00	0.986915E 00	0.899615E 00
9	0.455580E-02	0.886578E-02	0.159567E-00	0.990483E 00	0.926803E 00
12	0.763938E-02	0.149098E-01	0.162508E-00	0.994984E 00	0.961202E 00
15	0.110600E-01	0.216012E-01	0.165779E-00	0.999980E 00	0.999515E 00
18	0.144833E-01	0.283068E-01	0.169061E-00	0.100498E 01	0.103801E 01
21	0.175736E-01	0.343680E-01	0.172032E-00	0.100951E 01	0.107290E 01
24	0.200276E-01	0.391863E-01	0.174396E-00	0.101310E 01	0.110068E 01
27	0.216038E-01	0.422835E-01	0.175917E-00	0.101541E 01	0.111857E 01
30	0.221471E-01	0.433514E-01	0.176442E-00	0.101620E 01	0.112474E 01
SLUG FLOW					
0	-0.	-0.	0.161016E-00	0.992699E 00	0.943750E 00
3	0.244889E-03	0.481814E-03	0.161253E-00	0.993057E 00	0.946540E 00
6	0.955390E-03	0.187900E-02	0.161939E-00	0.994098E 00	0.954623E 00
9	0.206144E-02	0.405196E-02	0.163006E-00	0.995718E 00	0.967170E 00
12	0.345415E-02	0.678447E-02	0.164346E-00	0.997755E 00	0.982907E 00
15	0.499667E-02	0.780627E-02	0.165825E-00	0.100001E 01	0.100026E 01
18	0.653782E-02	0.128205E-01	0.167298E-00	0.100226E 01	0.101751E 01
21	0.792695E-02	0.155333E-01	0.168622E-00	0.100429E 01	0.103299E 01
24	0.902657E-02	0.176819E-01	0.169669E-00	0.100590E 01	0.104522E 01
27	0.973549E-02	0.190543E-01	0.170339E-00	0.100693E 01	0.105304E 01
30	0.997901E-02	0.195336E-01	0.170570E-00	0.100728E 01	0.105574E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.75$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.160005E-00	0.991138E 00	0.931985E 00
3	0.296742E-03	0.580306E-03	0.160288E-00	0.991572E 00	0.935306E 00
6	0.115796E-02	0.226467E-02	0.161111E-00	0.992830E 00	0.944946E 00
9	0.249948E-02	0.488885E-02	0.162394E-00	0.994789E 00	0.959970E 00
12	0.419010E-02	0.819678E-02	0.164011E-00	0.997259E 00	0.978918E 00
15	0.606447E-02	0.118653E-01	0.165806E-00	0.999998E 00	0.999943E 00
18	0.793914E-02	0.155354E-01	0.167601E-00	0.100274E 01	0.102099E 01
21	0.963056E-02	0.188477E-01	0.169222E-00	0.100521E 01	0.104000E 01
24	0.109731E-01	0.214773E-01	0.170509E-00	0.100717E 01	0.105509E 01
27	0.118351E-01	0.231660E-01	0.171336E-00	0.100843E 01	0.106479E 01
30	0.121321E-01	0.237480E-01	0.171621E-00	0.100887E 01	0.106813E 01
SLUG FLOW					
0	-0.	-0.	0.163026E-00	0.995759E 00	0.967358E 00
3	0.142195E-03	0.279293E-03	0.163163E-00	0.995967E 00	0.968970E 00
6	0.554787E-03	0.108941E-02	0.163561E-00	0.996571E 00	0.973642E 00
9	0.119719E-02	0.234995E-02	0.164179E-00	0.997511E 00	0.980904E 00
12	0.200627E-02	0.393617E-02	0.164956E-00	0.998694E 00	0.990025E 00
15	0.290264E-02	0.569171E-02	0.165815E-00	0.100000E 01	0.100010E 01
18	0.379848E-02	0.744431E-02	0.166672E-00	0.100131E 01	0.101014E 01
21	0.460617E-02	0.902285E-02	0.167443E-00	0.100249E 01	0.101916E 01
24	0.524685E-02	0.102739E-01	0.168053E-00	0.100343E 01	0.102630E 01
27	0.565804E-02	0.110763E-01	0.168445E-00	0.100403E 01	0.103087E 01
30	0.579971E-02	0.113527E-01	0.168579E-00	0.100423E 01	0.103244E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.833$, $b/c=0.50$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.165559E-00	0.999618E 00	0.997069E 00
3	0.127819E-04	0.250245E-04	0.165571E-00	0.999637E 00	0.997213E 00
6	0.498762E-04	0.976464E-04	0.165607E-00	0.999691E 00	0.997629E 00
9	0.107651E-03	0.210752E-03	0.165662E-00	0.999776E 00	0.998278E 00
12	0.180449E-03	0.353263E-03	0.165732E-00	0.999882E 00	0.999095E 00
15	0.261144E-03	0.511225E-03	0.165809E-00	0.100000E 01	0.100000E 01
18	0.341837E-03	0.669173E-03	0.165886E-00	0.100012E 01	0.100091E 01
21	0.414629E-03	0.811648E-03	0.165956E-00	0.100022E 01	0.100172E 01
24	0.472395E-03	0.924708E-03	0.166011E-00	0.100031E 01	0.100237E 01
27	0.509483E-03	0.997294E-03	0.166047E-00	0.100036E 01	0.100279E 01
30	0.522262E-03	0.102230E-02	0.166059E-00	0.100038E 01	0.100293E 01
SLUG FLOW					
0	-0.	-0.	0.165655E-00	0.999764E 00	0.998191E 00
3	0.789095E-05	0.154507E-04	0.165662E-00	0.999776E 00	0.998279E 00
6	0.307910E-04	0.602885E-04	0.165684E-00	0.999809E 00	0.998536E 00
9	0.664576E-04	0.130119E-03	0.165718E-00	0.999862E 00	0.998937E 00
12	0.111398E-03	0.218100E-03	0.165761E-00	0.999927E 00	0.999441E 00
15	0.161213E-03	0.315615E-03	0.165809E-00	0.100000E 01	0.100000E 01
18	0.211025E-03	0.413115E-03	0.165857E-00	0.100007E 01	0.100056E 01
21	0.255959E-03	0.501059E-03	0.165900E-00	0.100014E 01	0.100106E 01
24	0.291017E-03	0.570844E-03	0.165934E-00	0.100019E 01	0.100146E 01
27	0.314510E-03	0.615645E-03	0.165956E-00	0.100022E 01	0.100172E 01
30	0.322399E-03	0.631081E-03	0.165963E-00	0.100024E 01	0.100181E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.800$, $b/c=0.95$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.131699E-00	0.924218E 00	0.295425E-00
3	0.247439E-02	0.519604E-02	0.134421E-00	0.927644E 00	0.319162E-00
6	0.969218E-02	0.205755E-01	0.142583E-00	0.937691E 00	0.391676E-00
9	0.213436E-01	0.454409E-01	0.156096E-00	0.953657E 00	0.515887E 00
12	0.355382E-01	0.784076E-01	0.174569E-00	0.974330E 00	0.693219E 00
15	0.518558E-01	0.117153E-00	0.196996E-00	0.997975E 00	0.918512E 00
18	0.684382E-01	0.158274E-00	0.221535E-00	0.102239E 01	0.117527E 01
21	0.836257E-01	0.197444E-00	0.245517E-00	0.104509E 01	0.143453E 01
24	0.958335E-01	0.229940E-00	0.265805E-00	0.106356E 01	0.165905E 01
27	0.103744E-00	0.251462E-00	0.279417E-00	0.107563E 01	0.181191E 01
30	0.106483E-00	0.258991E-00	0.284213E-00	0.107983E 01	0.186614E 01

SLUG FLOW					
0	-0.	-0.	0.166034E-00	0.962965E 00	0.623576E 00
3	0.124392E-02	0.307036E-02	0.167860E-00	0.964793E 00	0.642621E 00
6	0.485190E-02	0.119616E-01	0.173144E-00	0.970092E 00	0.697652E 00
9	0.104655E-01	0.257570E-01	0.181325E-00	0.978328E 00	0.782659E 00
12	0.175287E-01	0.430473E-01	0.191553E-00	0.988677E 00	0.888548E 00
15	0.253448E-01	0.620933E-01	0.202782E-00	0.100011E 01	0.100434E 01
18	0.331469E-01	0.810131E-01	0.213900E-00	0.101150E 01	0.111847E 01
21	0.401730E-01	0.979735E-01	0.223834E-00	0.102174E 01	0.122002E 01
24	0.457409E-01	0.111361E-00	0.231654E-00	0.102984E 01	0.129966E 01
27	0.493119E-01	0.119923E-00	0.236645E-00	0.103503E 01	0.135037E 01
30	0.505417E-01	0.122868E-00	0.238360E-00	0.103682E 01	0.136776E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.800$, $b/c=0.92$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.151090E-00	0.946130E 00	0.480738E-00
3	0.177940E-02	0.399331E-02	0.153304E-00	0.948655E 00	0.501684E 00
6	0.695799E-02	0.157121E-01	0.159844E-00	0.956027E 00	0.564168E 00
9	0.150669E-01	0.343498E-01	0.170372E-00	0.967634E 00	0.666545E 00
12	0.253595E-01	0.585039E-01	0.184234E-00	0.982479E 00	0.804368E 00
15	0.368661E-01	0.861502E-01	0.200374E-00	0.999219E 00	0.968650E 00
18	0.484748E-01	0.114709E-00	0.217323E-00	0.101626E 01	0.114495E 01
21	0.590347E-01	0.141248E-00	0.233303E-00	0.103188E 01	0.131419E 01
24	0.674739E-01	0.162829E-00	0.246445E-00	0.104446E 01	0.145526E 01
27	0.729197E-01	0.176925E-00	0.255095E-00	0.105261E 01	0.154893E 01
30	0.748012E-01	0.181825E-00	0.258114E-00	0.105543E 01	0.158176E 01

SLUG FLOW					
0	-0.	-0.	0.179019E-00	0.976136E 00	0.757783E 00
3	0.801166E-03	0.197267E-02	0.180190E-00	0.977313E 00	0.769976E 00
6	0.312515E-02	0.768771E-02	0.183581E-00	0.980723E 00	0.805231E 00
9	0.674160E-02	0.165599E-01	0.188837E-00	0.986026E 00	0.859754E 00
12	0.112930E-01	0.276890E-01	0.195415E-00	0.992691E 00	0.927790E 00
15	0.163310E-01	0.399604E-01	0.202648E-00	0.100006E 01	0.100235E 01
18	0.213613E-01	0.521637E-01	0.209821E-00	0.100740E 01	0.107601E 01
21	0.258926E-01	0.631143E-01	0.216240E-00	0.101401E 01	0.114169E 01
24	0.294843E-01	0.717659E-01	0.221303E-00	0.101924E 01	0.119332E 01
27	0.317883E-01	0.773025E-01	0.224533E-00	0.102259E 01	0.122623E 01
30	0.325818E-01	0.792070E-01	0.225644E-00	0.102375E 01	0.123753E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.89$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.166136E-00	0.962356E 00	0.629595E 00
3	0.125150E-02	0.291601E-02	0.167800E-00	0.964157E 00	0.646010E 00
6	0.488900E-02	0.114290E-01	0.172676E-00	0.969398E 00	0.694326E 00
9	0.105707E-01	0.248368E-01	0.180402E-00	0.977610E 00	0.771566E 00
12	0.177582E-01	0.419868E-01	0.190364E-00	0.988040E 00	0.872295E 00
15	0.257619E-01	0.613260E-01	0.201700E-00	0.999708E 00	0.968304E 00
18	0.338038E-01	0.810052E-01	0.213337E-00	0.101149E 01	0.110879E 01
21	0.410911E-01	0.990450E-01	0.224090E-00	0.102221E 01	0.122122E 01
24	0.468962E-01	0.113552E-00	0.232792E-00	0.103078E 01	0.131291E 01
27	0.506335E-01	0.122954E-00	0.238456E-00	0.103632E 01	0.137296E 01
30	0.519231E-01	0.126209E-00	0.240422E-00	0.103823E 01	0.139377E 01

SLUG FLOW					
0	-0.	-0.	0.186628E-00	0.983861E 00	0.836394E 00
3	0.541638E-03	0.133070E-02	0.187417E-00	0.984656E 00	0.844591E 00
6	0.211280E-02	0.518697E-02	0.189702E-00	0.986960E 00	0.868307E 00
9	0.455818E-02	0.111769E-01	0.193247E-00	0.990543E 00	0.905028E 00
12	0.763639E-02	0.186963E-01	0.197688E-00	0.995050E 00	0.950923E 00
15	0.110445E-01	0.269950E-01	0.202578E-00	0.100003E 01	0.100132E 01
18	0.144484E-01	0.352554E-01	0.207435E-00	0.100500E 01	0.105121E 01
21	0.175153E-01	0.426747E-01	0.211787E-00	0.100948E 01	0.109579E 01
24	0.199468E-01	0.485409E-01	0.215222E-00	0.101302E 01	0.113088E 01
27	0.215068E-01	0.522970E-01	0.217418E-00	0.101529E 01	0.115328E 01
30	0.220441E-01	0.535895E-01	0.218173E-00	0.101607E 01	0.116097E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.86$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.177053E-00	0.973835E 00	0.739618E 00
3	0.872951E-03	0.207587E-02	0.178256E-00	0.975101E 00	0.751734E 00
6	0.340836E-02	0.811884E-02	0.181764E-00	0.978779E 00	0.787145E 00
9	0.736326E-02	0.175855E-01	0.187274E-00	0.984525E 00	0.843032E 00
12	0.123570E-01	0.296077E-01	0.194304E-00	0.991795E 00	0.914702E 00
15	0.179058E-01	0.430542E-01	0.202202E-00	0.999894E 00	0.995739E 00
18	0.234685E-01	0.566246E-01	0.210209E-00	0.100803E 01	0.107840E 01
21	0.284986E-01	0.689709E-01	0.217526E-00	0.101541E 01	0.115434E 01
24	0.324985E-01	0.788382E-01	0.223393E-00	0.102129E 01	0.121549E 01
27	0.350703E-01	0.852053E-01	0.227188E-00	0.102507E 01	0.125516E 01
30	0.359571E-01	0.874049E-01	0.228501E-00	0.102638E 01	0.126892E 01

SLUG FLOW					
0	-0.	-0.	0.191453E-00	0.988763E 00	0.886211E 00
3	0.376971E-03	0.924432E-03	0.192000E-00	0.989316E 00	0.891889E 00
6	0.147063E-02	0.360407E-02	0.193586E-00	0.990919E 00	0.908324E 00
9	0.317302E-02	0.776836E-02	0.196048E-00	0.993412E 00	0.933797E 00
12	0.531635E-02	0.129995E-01	0.199136E-00	0.996549E 00	0.965684E 00
15	0.760792E-02	0.187774E-01	0.202540E-00	0.100002E 01	0.100075E 01
18	0.100610E-01	0.245334E-01	0.205925E-00	0.100348E 01	0.103553E 01
21	0.121979E-01	0.297074E-01	0.208962E-00	0.100660E 01	0.106667E 01
24	0.138924E-01	0.338010E-01	0.211361E-00	0.100907E 01	0.109121E 01
27	0.149796E-01	0.364234E-01	0.212897E-00	0.101065E 01	0.110689E 01
30	0.153542E-01	0.373260E-01	0.213425E-00	0.101120E 01	0.111228E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.83$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.184753E-00	0.981821E 00	0.817977E 00
3	0.607692E-03	0.146094E-02	0.185606E-00	0.982705E 00	0.826664E 00
6	0.237199E-02	0.570732E-02	0.188088E-00	0.985274E 00	0.851962E 00
9	0.512204E-02	0.123405E-01	0.191971E-00	0.989281E 00	0.891625E 00
12	0.859093E-02	0.207317E-01	0.196894E-00	0.994340E 00	0.942043E 00
15	0.124409E-01	0.300759E-01	0.202388E-00	0.999962E 00	0.998494E 00
18	0.162958E-01	0.394638E-01	0.207921E-00	0.100560E 01	0.105552E 01
21	0.197775E-01	0.479696E-01	0.212945E-00	0.101070E 01	0.110744E 01
24	0.225435E-01	0.547444E-01	0.216954E-00	0.101475E 01	0.114897E 01
27	0.243207E-01	0.591054E-01	0.219538E-00	0.101736E 01	0.117577E 01
30	0.249333E-01	0.606102E-01	0.220430E-00	0.101825E 01	0.118504E 01
SLUG FLOW					
0	-0.	-0.	0.194669E-00	0.992033E 00	0.919399E 00
3	0.267195E-03	0.654160E-03	0.195056E-00	0.992424E 00	0.923406E 00
6	0.104242E-02	0.255079E-02	0.196177E-00	0.993560E 00	0.935011E 00
9	0.224927E-02	0.549948E-02	0.197919E-00	0.995327E 00	0.953015E 00
12	0.376896E-02	0.920577E-02	0.200106E-00	0.997550E 00	0.975579E 00
15	0.545220E-02	0.133022E-01	0.202519E-00	0.100001E 01	0.100043E 01
18	0.713403E-02	0.173860E-01	0.204521E-00	0.100247E 01	0.102512E 01
21	0.865002E-02	0.210594E-01	0.207078E-00	0.100468E 01	0.104725E 01
24	0.985230E-02	0.234673E-01	0.208784E-00	0.100643E 01	0.106472E 01
27	0.106238E-01	0.253310E-01	0.209876E-00	0.100756E 01	0.107589E 01
30	0.108896E-01	0.264726E-01	0.210252E-00	0.100795E 01	0.107974E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.80$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.190123E-00	0.987349E 00	0.872918E 00
3	0.423320E-03	0.102360E-02	0.190723E-00	0.987967E 00	0.879064E 00
6	0.165208E-02	0.399641E-02	0.192467E-00	0.989759E 00	0.896928E 00
9	0.356662E-02	0.863311E-02	0.195190E-00	0.992553E 00	0.924839E 00
12	0.598029E-02	0.144867E-01	0.198630E-00	0.996077E 00	0.960156E 00
15	0.865744E-02	0.209898E-01	0.202455E-00	0.999987E 00	0.999494E 00
18	0.113362E-01	0.275075E-01	0.206294E-00	0.100390E 01	0.103902E 01
21	0.137542E-01	0.335996E-01	0.209768E-00	0.100744E 01	0.107485E 01
24	0.156741E-01	0.390839E-01	0.212533E-00	0.101025E 01	0.110338E 01
27	0.169072E-01	0.410952E-01	0.214311E-00	0.101205E 01	0.112175E 01
30	0.173322E-01	0.421335E-01	0.214924E-00	0.101268E 01	0.112809E 01
SLUG FLOW					
0	-0.	-0.	0.196885E-00	0.994288E 00	0.942258E 00
3	0.191520E-03	0.468238E-03	0.197162E-00	0.994568E 00	0.945120E 00
6	0.747216E-03	0.182607E-02	0.197964E-00	0.995382E 00	0.953412E 00
9	0.161239E-02	0.393786E-02	0.199211E-00	0.996648E 00	0.966286E 00
12	0.270197E-02	0.659352E-02	0.200777E-00	0.998242E 00	0.982437E 00
15	0.390901E-02	0.953041E-02	0.202506E-00	0.100001E 01	0.100025E 01
18	0.511524E-02	0.124600E-01	0.204230E-00	0.100177E 01	0.101797E 01
21	0.620269E-02	0.150967E-01	0.205779E-00	0.100336E 01	0.103387E 01
24	0.706523E-02	0.171850E-01	0.207035E-00	0.100461E 01	0.104643E 01
27	0.761879E-02	0.185238E-01	0.207790E-00	0.100542E 01	0.105448E 01
30	0.780950E-02	0.189848E-01	0.208060E-00	0.100570E 01	0.105724E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.75$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.195696E-00	0.993060E 00	0.930117E 00
3	0.232408E-03	0.564326E-03	0.196028E-00	0.993399E 00	0.933529E 00
6	0.906912E-03	0.220233E-02	0.196991E-00	0.994384E 00	0.943433E 00
9	0.195756E-02	0.475434E-02	0.198493E-00	0.995919E 00	0.958869E 00
12	0.328160E-02	0.797139E-02	0.200386E-00	0.997854E 00	0.978337E 00
15	0.474950E-02	0.115342E-01	0.202486E-00	0.999978E 00	0.999940E 00
18	0.621759E-02	0.151088E-01	0.204587E-00	0.100214E 01	0.102157E 01
21	0.754214E-02	0.183304E-01	0.206484E-00	0.100408E 01	0.104109E 01
24	0.859343E-02	0.208881E-01	0.207990E-00	0.100562E 01	0.105660E 01
27	0.926845E-02	0.225307E-01	0.208958E-00	0.100660E 01	0.106657E 01
30	0.950105E-02	0.230968E-01	0.209292E-00	0.100694E 01	0.107000E 01
SLUG FLOW					
0	-0.	-0.	0.199233E-00	0.996679E 00	0.966464E 00
3	0.111311E-03	0.271644E-03	0.196394E-00	0.996842E 00	0.968120E 00
6	0.434301E-03	0.105957E-02	0.199858E-00	0.997315E 00	0.972919E 00
9	0.937233E-03	0.228558E-02	0.200582E-00	0.998050E 00	0.980377E 00
12	0.157073E-02	0.382833E-02	0.201491E-00	0.998977E 00	0.989748E 00
15	0.227266E-02	0.553574E-02	0.202496E-00	0.100000E 01	0.100010E 01
18	0.297427E-02	0.724028E-02	0.203499E-00	0.100133E 01	0.101041E 01
21	0.360692E-02	0.877550E-02	0.204402E-00	0.100195E 01	0.101968E 01
24	0.410881E-02	0.994221E-02	0.205117E-00	0.100268E 01	0.102702E 01
27	0.443095E-02	0.107726E-01	0.205575E-00	0.100315E 01	0.103172E 01
30	0.454194E-02	0.110414E-01	0.205733E-00	0.100332E 01	0.103334E 01

SUMMARY OF TEMPERATURE CALC. ($\kappa=1.102$, $\kappa_v=0.221$, $a/b=0.80$, $b/c=0.50$)

TEMPERATURES FOR ORDER 8

ANGLE	INSIDE WALL SURFACE TEMP	OUTSIDE WALL SURFACE TEMP	TEMP DROP ACROSS WALL	INSIDE WALL HEAT FLUX	OUTSIDE WALL HEAT FLUX
LAMINAR FLOW					
0	-0.	-0.	0.202197E-00	0.999701E 00	0.996987E 00
3	0.100156E-04	0.243527E-04	0.202211E-00	0.999716E 00	0.997134E 00
6	0.390817E-04	0.950250E-04	0.202253E-00	0.999758E 00	0.997563E 00
9	0.843527E-04	0.205094E-03	0.202318E-00	0.999824E 00	0.998229E 00
12	0.141396E-03	0.343779E-03	0.202399E-00	0.999908E 00	0.999069E 00
15	0.204628E-03	0.497499E-03	0.202490E-00	0.100000E 01	0.100000E 01
18	0.267858E-03	0.651205E-03	0.202580E-00	0.100009E 01	0.100093E 01
21	0.324898E-03	0.789854E-03	0.202662E-00	0.100018E 01	0.100177E 01
24	0.370164E-03	0.899879E-03	0.202726E-00	0.100024E 01	0.100244E 01
27	0.399226E-03	0.970515E-03	0.202768E-00	0.100028E 01	0.100286E 01
30	0.409240E-03	0.994854E-03	0.202782E-00	0.100030E 01	0.100301E 01
SLUG FLOW					
0	-0.	-0.	0.202309E-00	0.999815E 00	0.998140E 00
3	0.618306E-05	0.150360E-04	0.202318E-00	0.999824E 00	0.998231E 00
6	0.241268E-04	0.586702E-04	0.202343E-00	0.999851E 00	0.998495E 00
9	0.520741E-04	0.126626E-03	0.202383E-00	0.999892E 00	0.998907E 00
12	0.872886E-04	0.212745E-03	0.202434E-00	0.999943E 00	0.999426E 00
15	0.126323E-03	0.307141E-03	0.202490E-00	0.100000E 01	0.100000E 01
18	0.165355E-03	0.402023E-03	0.202545E-00	0.100006E 01	0.100058E 01
21	0.200566E-03	0.487606E-03	0.202596E-00	0.100011E 01	0.100109E 01
24	0.228508E-03	0.555516E-03	0.202636E-00	0.100015E 01	0.100150E 01
27	0.246447E-03	0.599113E-03	0.202661E-00	0.100018E 01	0.100177E 01
30	0.252629E-03	0.614135E-03	0.202670E-00	0.100018E 01	0.100186E 01

APPENDIX A

DERIVATION OF NEUMANN BOUNDARY CONDITIONS ON THE LINE $r = c/\cos(\phi)$

Let $\vec{e}_r$ and $\vec{e}_\phi$ be unit vectors in the radial and azimuthal directions, respectively, for planar cylindrical coordinates. Then $\vec{e}_r = \cos\phi \vec{i} + \sin\phi \vec{j}$, and $\vec{e}_\phi = -\sin\phi \vec{i} + \cos\phi \vec{j}$ when $\vec{i}$ and $\vec{j}$ are Cartesian unit vectors. From Fig. 1 the unit vector $\vec{n}$ normal to the line $r = c/\cos\phi$ is $\vec{n} = \vec{i}$. As

$$\text{grad } T = \frac{\partial T}{\partial r} \vec{e}_r + \frac{1}{r} \frac{\partial T}{\partial \phi} \vec{e}_\phi \quad (\text{A.1})$$

it follows that

$$\vec{n} \cdot \text{grad } T = \frac{\partial T}{\partial r} \vec{n} \cdot \vec{e}_r + \frac{1}{r} \frac{\partial T}{\partial \phi} \vec{n} \cdot \vec{e}_\phi \quad (\text{A.2})$$

But, $\vec{n} \cdot \vec{e}_r = \cos\phi$ and $\vec{n} \cdot \vec{e}_\phi = -\sin\phi$,

so that

$$\vec{n} \cdot \text{grad } T = \cos\phi \frac{\partial T}{\partial r} - \frac{\sin\phi}{r} \frac{\partial T}{\partial \phi} \quad (\text{A.3})$$

Evaluating equation (A.3) at $r = c/\cos\phi$ yields equation (17). An analogous derivation leads to equation (16).

APPENDIX B

DERIVATION OF THE GREEN'S FUNCTIONS FOR THE GENERAL SOLUTIONS OF THE FUEL REGION TEMPERATURE FIELD

The object of this appendix is to provide formal derivations of the Green's functions appearing in equations (20) and (22).

When $n = 0$, equation (18) becomes

$$\frac{1}{r} \frac{d}{dr} \left[r \frac{dv_c}{dr} (r, 0) \right] + \frac{q_c(r, 0)}{k} = 0. \quad (B.1)$$

The Green's function, K_0 , may formally be defined as a solution of the partial differential equation,

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dK_0}{dr} \right) + \frac{\delta(r - y)}{r} = 0 \quad (B.2)$$

where $\delta(r - y)$ is the Dirac delta function. Multiplying equation (B.1) through by K_0 and equation (B.2) through by $v_c(r, 0)$ and subtracting the results gives

$$v_c(r, 0) \frac{\delta(r - y)}{r} = \frac{K_0}{k} q_c(r, 0) + \frac{K_0}{r} \frac{d}{dr} \left[r \frac{dv_c}{dr} (r, 0) \right] - \frac{v_c(r, 0)}{r} \frac{d}{dr} \left(r \frac{dK_0}{dr} \right). \quad (B.3)$$

Operating on equation (B.3) produces

$$v_c(y,0) = (1/k) \int_0^a dr r q_c(r,0) K_0 \quad (B.4)$$

where we have used the fact that

$$\int_0^a dr \left\{ K_0 \frac{d}{dr} \left[r \frac{dv_c}{dr}(r,0) \right] - v_c(r,0) \frac{d}{dr} \left(r \frac{dK_0}{dr} \right) \right\} = 0 \quad (B.5)$$

provided the Green's function vanishes at $r = a$. In equation (B.5) we have also set $v_c(a,0) = 0$ as we are finding only a particular integral of equation (B.1) by the Green's function method. The fact that $v_c(r,0)$ is not actually zero at $r = a$ is taken into account by adding the solution, $(\pi/6)A_0 + (\pi/6)B_0 \ln(r)$, of the homogeneous counterpart of equation (B.1) to equation (B.4) to obtain the general solution of equation (B.1) as it appears in equation (19).

When $r \neq y$ the solution of equation (B.2) is $A' + B' \ln(r)$, where A' and B' are constants. From equation (B.2), we have

$$\lim_{\epsilon \rightarrow 0} \frac{dK_0}{dr} \bigg|_{y-\epsilon}^{y+\epsilon} = - \frac{1}{y} \quad (B.6)$$

as the Green's function is continuous at $r = y$. It is also finite at $r = 0$. Hence, it may be written in the form,

$$K_0 = \begin{cases} A & \text{if } r < y \\ B \ln(r/a) & \text{if } r > y \end{cases} \quad (B.7)$$

From the fact that the Green's function is continuous at $r = y$ with a discontinuous derivative as given by equation (B.6), we find that $B = -1$ and $A = -\ln(y/a)$. Therefore,

$$K_0 = \begin{cases} \ln(a/y) & \text{if } r < y \\ \ln(a/r) & \text{if } r > y \end{cases} \quad (\text{B.8})$$

as given in equation (20).

When $n = 1, 2, 3, \dots$, the Green's function, K_{6n} , for the differential operator appearing in equation (18) formally satisfies:

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dK_{6n}}{dr} \right) - \frac{36n^2}{r^2} K_{6n} + \frac{\delta(r - y)}{r} = 0. \quad (\text{B.9})$$

When $r \neq y$ a solution of equation (B.9) which remains finite at $r = 0$ is r^{6n} , and a solution which vanishes at $r = a$ is $(r/a)^{6n} - (a/r)^{6n}$. Hence, we have

$$K_{6n} = \begin{cases} A_{6n} r^{6n} & \text{if } r < y \\ B_{6n} \left[\left(\frac{r}{a} \right)^{6n} - \left(\frac{a}{r} \right)^{6n} \right] & \text{if } r > y \end{cases} \quad (\text{B.10})$$

As the derivative of K_{6n} is also discontinuous in the amount, $(-1/y)$ at $r = y$, this condition together with the requirement that the Green's function, K_{6n} , be continuous at $r = y$ leads to

$$A_{6n} = (-1/12na^{6n}) [(y/a)^{6n} - (a/y)^{6n}] \quad (\text{B.11})$$

and

$$B_{6n} = (-1/12n)(y/a)^{6n} . \quad (B.12)$$

Hence, we obtain

$$K_{6n} = \begin{cases} (1/12n)(r/a)^{6n} [(a/y)^{6n} - (y/a)^{6n}] & \text{if } r < y \\ (1/12n)(y/a)^{6n} [(a/r)^{6n} - (r/a)^{6n}] & \text{if } r > y \end{cases} \quad (B.13)$$

as given in equation (22). By following the same procedure with equations (18) and (B.9) as was used with equations (B.1) and (B.2), the particular integral term which appears in equation (21) is found.

SYMBOLS

c_p	Coolant specific heat
k	Fuel thermal conductivity
k_c	Coolant thermal conductivity
k_w	Tube wall thermal conductivity
p	Coolant pressure
t	Tube wall temperature field
T	Coolant temperature field
T_m	Coolant bulk mean temperature
u	Coolant velocity field
v	Fuel temperature field
w	Coolant mass flow rate
μ	Coolant viscosity
ρ	Coolant density

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