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Title : Monte Carlo Simulation of Radiation Heat Transfer in a Three-Dimensional Enclosure Containing a Circular Cylinder

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James R. Welty

The distribution of radiation heat flux within an enclosure containing a horizontal circular pipe, which also contains a medium which has absorbing, emitting and isotropic scattering characteristics was studied using the Monte Carlo method. The MCHO3D Monte Carlo code was developed for this three-dimensional geometry.

This study consisted of three parts. First, a comparison with results of previous work in one- and two-dimensional cases was conducted to validate the MCHO3D Monte Carlo code. The other two parts were conducted for the three-dimensional enclosure for the case without and with an absorbing and scattering medium present.

The bottom surface of the square enclosure was considered a uniform-heat flux surface and the other surfaces were considered cold. Enclosure surfaces were treated as black walls. A circular pipe was located in the center of the enclosure; its length varied with enclosure depth. In the second part of this study (cases 1, 2), different configurations were used with an optically thin ($\tau \ll 1$) medium in the enclosure, and for part 3 different optical thicknesses were used with a range of enclosure size.

The amount of radiative energy transferred to the enclosed pipe depends on its location, the optical thickness of the participating medium, and enclosure depth. For the optically thin cases ($\tau \ll 1$) the Monte Carlo solution calculates view factors which are generally applicable for geometric descriptions.

MONTE CARLO SIMULATION OF RADIATION HEAT TRANSFER IN A THREE - DIMENSIONAL ENCLOSURE CONTAINING A CIRCULAR CYLINDER

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NOMENCLATURE

a_n	scattering phase function coefficients
A_i	area of surface i of enclosure
D	diameter of pipe
E	emissive power
E_b	blackbody emissive power
G	incident radiation
I	intensity of radiation
L	path length
N	number of emitted bundles per unit volume or area
N_{total}	total number of bundle emited from wall 1
P	probability function
P_n	Legendre polynomials
Q_1	emissive power of wall 1
$\acute{r}$	unit vector into a given direction
R	random number
s	path length
SN_i	total number of absorptions in given area element
T	Temperature
ΔV	volume element
x	horizontal direction
X	horizontal length of enclosure
y	direction in enclosure depth
Y	depth of enclosure
z	vertical direction
Z	vertical length of enclosure
α	absorptance or absorptivity
β	extinction coefficient

ϵ	emittance or emissivity
θ	polar angle
κ	absorption coefficient
σ	Stefan - Boltznann constant
σ_s	scattering coefficient
τ	optical thickness
ϕ	azimuthal angle
ω	energy per photon bundle
ω	single scattering albedo
Φ	scattering phase function
Φ_P, Φ_b	dimensionless temperature in medium
φ_P	dimensionless emissive power in medium
Ψ_P	dimensionless radiative heat flux
Ω'	solid angle

Subscriptions

i	incident, incoming
e	emitted, outgoing
g	gas, medium
p	medium increment index
1,2,x,y,z	in a given direction
λ	at a given wavelength, or per unit wavelength
λ	wavelength dependent
θ, ϕ	in a given direction

Superscripts

/	directional quantity or dummy variable
*	dummy variable

MONTE CARLO SIMULATION OF RADIATION HEAT TRANSFER IN A THREE-DIMENSIONAL ENCLOSURE CONTAINING A CIRCULAR CYLINDER

CHAPTER 1

INTRODUCTION

In any process involving high temperatures such as heat treatment, power generation, and other large-scale industrial applications, radiation heat transfer is an important mechanism in addition to convection and conduction. Many investigators have studied radiation heat transfer problems over the past several decades.

Early radiation research was confined to one-dimensional cases involving absorbing, emitting, and/or isotropic scattering media [1,2,3]. As one-dimensional analyses of radiative heat transfer are often inadequate, it has been necessary to broaden the research to include multidimensional geometries. In recent years many studies have dealt with multidimensional enclosures with absorbing, emitting, and scattering media present. Most of these studies were focused on solving the radiative transfer equation with few parametric studies on design factors in simple enclosures. It has been the purpose of the present study to determine appropriate parameters to describe radiant transfer in a geometry of practical interest.

A variety of computational tools for analyzing radiative heat transfer

problems have been proposed in the past several decades. Each of the methods developed has been successfully applied to simple one-dimensional gray problems. However, no single method is now accepted as being the best for all complicated problems. One of the more popular current methods is the Monte Carlo method [4,5,6,7,8], a statistical method in which the history of large numbers of photon bundles is traced. The Monte Carlo method has the advantage that almost any problem of arbitrary complexity can be addressed with relative ease, but has the disadvantages of statistical scatter in the results and its large appetite for computer time. With the developments in computer technology the second disadvantage is disappearing, and we can expect more accurate and faster results from these kinds of simulations.

In this paper a square duct with a centered, circular pipe as shown in figure 1, was examined, and the relevant heat exchange between surfaces was determined using the Monte Carlo method. The bottom surface of the square enclosure was considered a uniform-heat flux surface; it radiated to walls considered cool enough so their emission was small, with their surfaces rough and soot-covered so they were treated as black walls. A circular pipe was located in the enclosure and its length varied with enclosure depth.

In cases 1 and 2, different configurations were used with an optically thin medium in the enclosure. In cases 3 and 4, different optical thicknesses were used for a range of enclosure depths. Through these simulations useful design factors were obtained and presented parametrically.

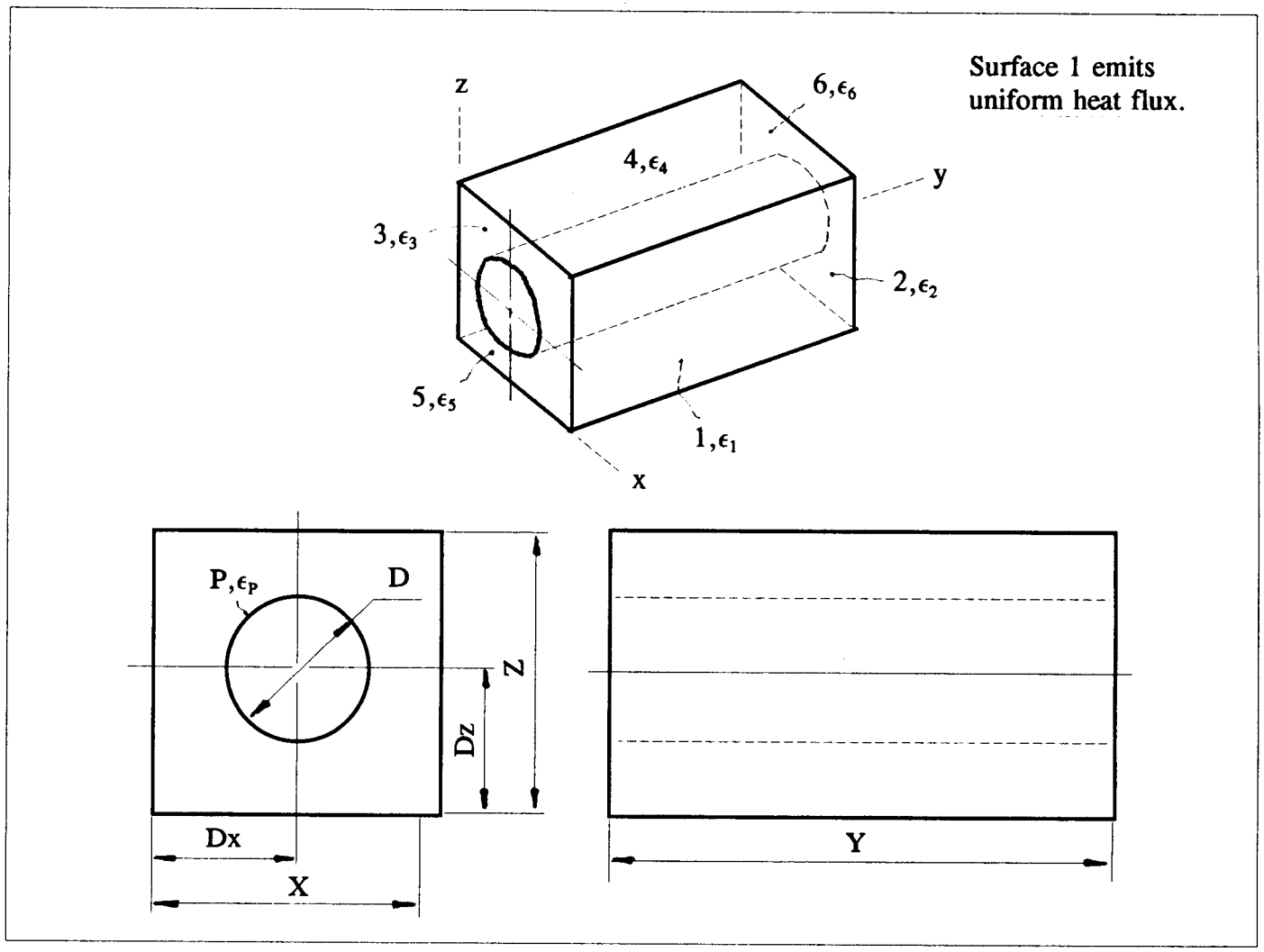


Figure 1. Geometrical configuration.

CHAPTER 2

MONTE CARLO METHOD

2.1. Introduction and Definition

There are several different computational methods with which radiative heat transfer problems may be analyzed. One of the more popular ones is the Monte Carlo method, a statistical method in which the history of large numbers of photon bundles is traced.

A good definition for the Monte Carlo method has been given by Kahn [9], who wrote " The expected score of a player in any reasonable game of chance, however complicated, can in principle be estimated by averaging the results of a large number of plays of the game. Such estimation can be rendered more efficient by various devices which replace the game with another known to have the same expected score. The new game may lead to a more efficient estimate by being less erratic, that is, having a score of lower variance or by being cheaper to play with the equipment on hand. There are obviously many problems about probability that can be viewed as problems of calculating the expected score of a game. Still more, there are problems that do not concern probability but are none the less equivalent for some purposes to the calculation of an expected score. The Monte Carlo method refers simply to the exploitation of these remarks."

This definition also gives us a good opportunity to apply this method to

other areas. Indeed what must be done for a specific problem is to set up a game or model that obeys the same behavior and hence is expected to produce the same outcome as the physical problem which the model simulates; make the game as simple and fast to play as possible; then play the game many times and find the average outcome. After some remarks on previous uses of the method, this formalism will be applied to the given application in radiative heat transfer.

2. 2. Review of the Monte Carlo method in Radiative Heat Transfer Analyses

Like several other radiative heat transfer models, the Monte Carlo method was first employed in the field of neutron transport, for the development of the atomic bomb during World War II. The first radiative heat transfer papers using this method were published by Howell and Perlmutter [2], and Perlmutter and Howell [10]. They treated radiation through gases in simple geometries such as plane walls and concentric cylinders. Subsequently many investigators, Fleck [11], Howell at al [12], for example, have used the method to solve more practical problems.

Recent applications of the Monte Carlo method have appeared that exploit its flexibility and power to examine difficult problems. A few of these can be cited to give the overall flavor of these applications. Slater et al.[13], Bernes [14], Meier and Lee [15], Katkovskii et al.[16], and Vlasov and Titarchuk [17] all have used Monte Carlo approaches to solve problems in which the medium was not assumed to be in local thermodynamic equilibrium (LTE). Carter et al.[18] used

the method to include the effects of polarization on radiative transfer. Egan and Hilgeman[19] examined the spectral reflectance of particulates. Dunn [20] has applied the method to nonhomogeneous media. Gupta et al.[21] included anisotropic scattering in their Monte Carlo analysis of coal furnaces with fly-ash. Lewis and Miller [22] and Meier et al.[23] have presented valuable information on Monte Carlo applications in scattering problems.

2.3. Advantages and Disadvantages of the Monte Carlo method

The advantage of the Monte Carlo method is in its flexibility. It is extremely useful when (1) there is no other convenient method, (2) a simple procedure is needed to check the validity of a new method, and (3), in some instances, a computationally faster procedure is needed[Haji-Sheikh,8]. Indeed, it is refreshing to see that Monte Carlo program complexity increases roughly in proportion to problem complexity for radiative interchange problems. As the complexity of the problem increases, however, the complexity of formulation and the solution effort increase much more rapidly for conventional techniques. For problems beyond a certain complexity, the Monte Carlo solution will be preferable, as schematically indicated in Figure 2 [Modest, 7]. As mentioned by Modest, there is no way to determine a priori precisely where this crossover point in complexity lies.

Another disadvantage of Monte Carlo methods is that, as with other statistical methods, the results calculated fluctuate around the real answer, similar

to the unavoidable error associated with experimental measurements, because the method is a repetitive experiment using a mathematical model in place of the actual physical situation. The uncertainty can be found by applying standard statistical tests; the uncertainty can be reduced in the same manner as experimental error,

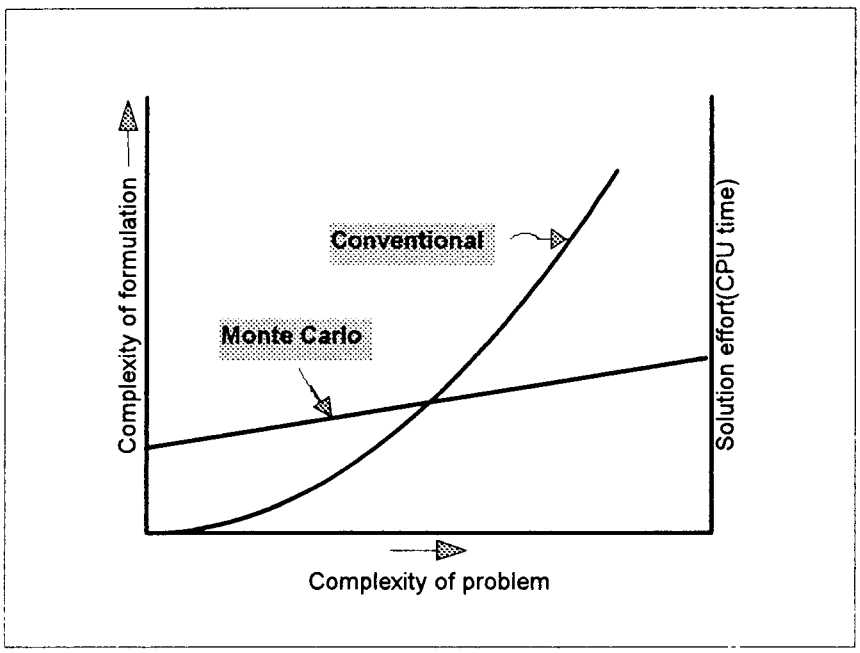


Figure 2. Comparison of Monte Carlo and conventional solution techniques [Modest,7].

that is, by averaging over more tests (bundle histories in radiative problems).

No rigorous criteria exist to guarantee the convergence of Monte Carlo results to a valid solution; however, convergence has not as yet been a difficulty in thermal radiation problems. It would be immediately evident that convergence to invalid solutions was occurring because of the limiting solutions and physical

constraints that are known for most radiative problems. It should be noted that the latter fault is common to many methods when complex problems are being treated because rigorous mathematical criteria to guarantee convergence to a solution is available only in certain cases.

2.4. Monte Carlo method in Radiative Heat Transfer

2.4.1. Probability Distributions

In order to follow the history of radiative energy bundles in a statistically meaningful way, the points, directions and wavelengths of emission, reflective behavior, etc. must be chosen according to probability distributions.

As an example, consider the total radiative heat flux being emitted from a surface, i.e., the total emissive power,

$$E = \int_0^\infty E_\lambda d\lambda = \int_0^\infty \epsilon_\lambda E_{b\lambda} d\lambda \tag{1}$$

Between the wavelengths of λ and $\lambda + d\lambda$ the emitted heat flux is $E_\lambda d\lambda = \epsilon_\lambda E_{b\lambda} d\lambda$ and the fraction of energy emitted over this wavelength range is

$$P(\lambda)d\lambda = \frac{E_\lambda d\lambda}{\int_0^\infty E_\lambda d\lambda} = \frac{E_\lambda}{E} d\lambda \tag{2}$$

We may think of all the photons leaving the surface as belonging to a set of N energy bundles of equal energy (each consisting of many photons of a single

wavelength). Then each bundle carries the amount of energy (E/N) with it, and the probability that any particular bundle has a wavelength between λ and $\lambda + d\lambda$ is given by the probability density function $P(\lambda)$. The fraction of energy emitted over all wavelengths between 0 and λ is then

$$R(\lambda) = \int_0^{\infty} P(\lambda)\, d\lambda = \frac{\int_0^{\lambda} E_\lambda d\lambda}{\int_0^{\infty} E_\lambda d\lambda} \qquad (3)$$

It is immediately obvious that $R(\lambda)$ is also the probability that any given energy bundle has a wavelength between 0 and λ, and it is known as the cumulative distribution function. The probability that a bundle has a wavelength between 0 and ∞ is, of course, $R(\lambda \rightarrow \infty) = 1$, a certainty. Equation (3) implies that if we want to simulate emission from a surface with N energy bundles of equal energy, then the fraction $R(\lambda)$ of these bundles must have wavelengths smaller than λ.

2.4.2. Random Number Relations

In the Monte Carlo method a large statistical sample of photon energy bundles are traced from their point of emission to their point of absorption (or their leaving the geometry under investigation). To obtain statistically meaningful results, relations need to be developed between random numbers and points of

emission (from a surface, or from within the medium), direction of emission, wavenumber of emission, distance traveled before absorption (within the medium), distance traveled before scattering, scattering direction, probability of reflection from a surface, and reflection direction.

2.4.2.1. Emission Points of Bundle

In a two dimensional plane-surface system, for example, the relationship between random number, R, and given length of system, X or Y, may be inverted to find the x or y location of the emission point. Similar to equation (3) we may write the cumulative distribution function for emission point x, y as

$$R_x = \frac{\int_0^x E_x(x)\,dx}{\int_0^X E_x(x)\,dx} \tag{4}$$

$$R_y = \frac{\int_0^y E_y(y)\,dy}{\int_0^Y E_y(y)\,dy} \tag{5}$$

respectively. In the simplest case of an isothermal surface with constant emissivity, these relations reduce to

$$x = R_x X, \qquad y = R_y Y. \tag{6}$$

2.4.2.2. Choosing the Direction of Emission

To choose the direction of emission from an emission point or reflecting point the probability of emission into a particular direction is used. Two angles must be specified, the polar angle θ and azimuthal angle ϕ.

The probability density function $P(\theta)$ over all wavelengths and azimuthal angles is

$$\begin{aligned} P(\theta)\, d\theta &= d\theta \int_0^{2\pi} \int_0^{\lambda} P(\lambda,\theta,\phi)\, d\lambda\, d\phi \\ &= \frac{2\epsilon'(\theta)\cos\theta\ \sin\theta\, d\theta}{\epsilon} \end{aligned} \tag{7}$$

Integrating equation (7) with respect to θ between 0 and θ, the cumulative probability function is

$$R(\theta) = \int_0^{\theta} P(\theta^*)\, d\theta^* = \frac{2\int_0^{\theta} \epsilon'(\theta^*) \sin\theta^* \cos\theta^*\, d\theta^*}{\epsilon} \tag{8}$$

For a diffuse gray emitter equation(8) reduces to

$$\begin{aligned} R(\theta)_{,diffuse} &= 2\int_0^{\theta} \sin\theta^* \cos\theta^*\, d\theta^* \\ &= \sin^2\theta \end{aligned} \tag{9}$$

or

$$\theta = \sin^{-1}(R(\theta)_{,diffuse})^{1/2} \tag{10}$$

Similar arguments apply to the determination of the azimuthal angle, ϕ,

$$R(\phi) = \frac{\phi}{2\pi} \qquad or \qquad \phi = 2\pi R(\phi) \tag{11}$$

2.4.2.3. Absorption and Reflection

When radiative energy impinges on a surface, the fraction α'_λ will be absorbed, which may depend on the wavelength of irradiation, the direction of the incoming rays, and, perhaps, the local temperature. Of many incoming bundles the fraction α'_λ will therefore be absorbed while the rest, $1 - \alpha'_\lambda$, will be reflected. This can clearly be simulated by picking a random number, R_α , and comparing with α'_λ ;

$$\begin{aligned} R(\alpha) &\le \alpha'_\lambda \qquad (absorbed) \\ R(\alpha) &> \alpha'_\lambda \qquad (reflected) \end{aligned} \tag{12}$$

2.4.2.4. Directions for Emission from within Medium

Under local thermodynamic equilibrium conditions emission within a participation medium is isotropic, i.e., all possible directions are equally likely for the emission of a photon. All possible directions from a point within the medium, are contained within the solid angle of $4\pi = \int_0^{2\pi}\int_0^{\lambda}\sin\theta \, d\theta \, d\phi$

The probability distribution for emission corresponding to angle θ is given by

$$P(\theta) = \frac{\sin\theta\, d\theta}{\int_0^{\pi} \sin\theta\, d\theta} \tag{13}$$

The cumulative distribution function then becomes

$$R(\theta) = \frac{1}{2}\int_0^{\theta} \sin\theta^{*}\, d\theta^{*} = \frac{1}{2}(1 - \cos\theta) \tag{14}$$

or, the angle θ can be expressed as

$$\theta = \cos^{-1}(1 - 2R(\theta)) \tag{15}$$

Similarly

$$R(\phi) = \frac{\phi}{2\pi} \qquad or \qquad \phi = 2\pi R(\phi) \tag{16}$$

Here, the polar angle, θ, and azimuthal angle, ϕ, are measured from arbitrary reference coordinates.

2.4.2.5. Path Length of Bundle within Medium

If the medium through which radiative energy travels is participating, then any incident beam will be attenuated by absorption and scattering. Equation (17) gives the absorptivity for the participating medium (for a given path within the medium) as

$$\alpha_{\lambda} = 1 - \exp\left(-\int_0^{S} \kappa_{\lambda}\, ds\right) \tag{17}$$

Here we can replace α_{λ} by a random number from 0 to 1. Therefore the path

length of a certain bundle within the absorbing medium is

$$L_\kappa = -\frac{1}{\kappa_\lambda}\ln[1 - R(\kappa)] \tag{18}$$

Since R(s) is uniformly distributed between 0 and 1, this relation may as well as written as

$$L_\kappa = -\frac{1}{\kappa_\lambda}\ln R(\kappa) \tag{19}$$

According to this relation, the bundle is allowed to travel a total distance, L_κ, through the medium before being absorbed.

Scattering will also attenuate the bundle intensity. The same relationships apply to the scattering cases as for absorption, thus

$$L_\sigma = -\frac{1}{\sigma_{s\lambda}}\ln R(\sigma_s) \tag{20}$$

is the distance a bundle travels in a medium with uniform scattering coefficient before being scattered, or

$$\int_0^l \sigma_{s\lambda}\, ds < \int_0^L \sigma_{s\lambda}\, ds = \ln\frac{1}{R(\sigma_s)} \tag{21}$$

for a medium with nonuniform scattering coefficient.

Here, we can use the useful conception, extinction. The total attenuation of the beam by both absorption and scattering is calculated introducing the extinction coefficient which is defined as

$$\beta_\lambda = \kappa_\lambda + \sigma_{s\lambda} \tag{22}$$

so that equation (17) becomes

$$\alpha_\lambda = 1 - \exp\left[-\int_0^L \beta_\lambda dL\right] \tag{23}$$

and the path length is

$$L_\beta = -\frac{1}{\beta_\lambda} \ln R(\beta) \tag{24}$$

within an absorbing and scattering medium.

For a given geometry there is another useful dimensionless quantity

$$\tau_\lambda(S) = \int_0^S \beta_\lambda(S^*) dS^* \tag{25}$$

The quantity τ(S) is the optical thickness or opacity of the layer of given thickness S. The optical thickness is a measure of the ability of a path length to attenuate radiation of a given wavelength. A large optical thickness means large attenuation.

For a medium with uniform composition and at uniform temperature and pressure equation (25) becomes

$$\tau_\lambda(S) = \beta_\lambda S \tag{26}$$

So that the path length based on given thickness of certain geometry is

$$s_\tau = -\frac{1}{\tau_\lambda(S)} \ln R(\tau) \tag{27}$$

2.5. Equations for Solutions

2.5.1. Net Heat Transfer to Surfaces

The general solution for different surface temperatures and emissivities is as follows. Referring to figure 3, the energy exchange between surfaces can be written

$$
\begin{aligned}
q_{1,net} &= \sum_{j=1}^{n} q_{j-1} + q_{g-1} - \sum_{j=1}^{n} q_{1-j} \\
&= \sum_{j=1}^{n} SN_{j-1}\omega_j + SN_{g-1}\omega_g - \sum_{j=1}^{n} SN_{1-j}\omega_1 \\
&= \sum_{j=1}^{n} SN_{j-1}\frac{\epsilon_j Q_{b,j}}{N_j} + SN_{g-1}\frac{\epsilon_g Q_{b,g}}{N_g} - \sum_{j=1}^{n} SN_{1-j}\frac{\epsilon_1 Q_{b,1}}{N_1}
\end{aligned}
\tag{28}
$$

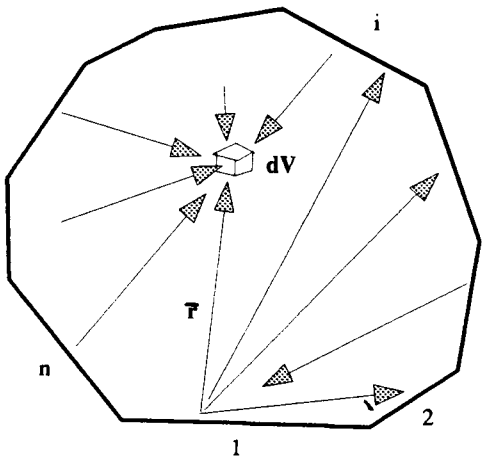


Figure 3. Inclosure composed of n discrete surface areas and filled with uniform gas with radiation mode

If there are no heat sources in the gas and walls except wall 1, the net radiation heat transfer between surface 1 and the other walls is

$$q_{1,net} = -\sum_{j=1}^{n} SN_{1-j}\frac{\epsilon_1 Q_{b,1}}{N_1} \tag{29}$$

Therefore the dimensionless radiation heat flux for each wall is

$$\frac{q_{i,net}}{q_1} = \frac{SN_i}{N_1} \qquad \text{(i=1,2,3,4,5,6,P)} \tag{30}$$

2.5.2. Gas Emissive Power Distribution

The emissive power distribution for the case of a gas with a uniform heat source, enclosed within walls of different temperatures and emissivities is

$$\begin{aligned} 4\tau\sigma T_{g,\bar{r}}^4 \Delta V &= \omega_g(\Delta V N_g + SN_{g-g,\bar{r}}) + \sum_{i=1}^{n} SN_{i-g,\bar{r}}\omega_i \\ &= \sum_{i=1}^{n} \frac{SN_{i-g,\bar{r}}\,\epsilon_i Q_{b,i}}{N_i} + Q_g\left(\Delta V + \frac{SN_{g-g,\bar{r}}}{N_g}\right) \end{aligned} \tag{31}$$

where the left hand term, $4\tau\sigma T_{g,r}^4 \Delta V$, is given by Jakob [30] and ω is the energy per bundle.

If there is no heat source in the medium and wall emissivities are equal, equation (31) becomes

$$4\tau\sigma T_{g,\bar{r}}^{4}\,\Delta V = \epsilon \sum_{i=1}^{n} \frac{SN_{i-g,\bar{r}}\,Q_{b,i}}{N_i} \tag{32}$$

In this work there are no wall heat sources except at wall 1, thus equation (32) becomes

$$4\tau\sigma T_{g,\bar{r}}^{4}\,\Delta V = \frac{SN_{1-g}}{N_1}\,\epsilon\,Q_{b,1} \tag{33}$$

CHAPTER 3

NUMERICAL ANALYSIS

The Fortran code, MCHO3D[Appendix 1] was developed for analyzing radiative heat transfer for the configuration shown in figure 1. In chapter 2 details of the Monte Carlo method, as applied to thermal radiation problems, were given. In this chapter, the Monte Carlo solution procedure used in this research will be described.

For the numerical study, the enclosure and circular pipe were subdivided into 20×20×20, and 20×20 segments respectively as illustrated in figure 4.

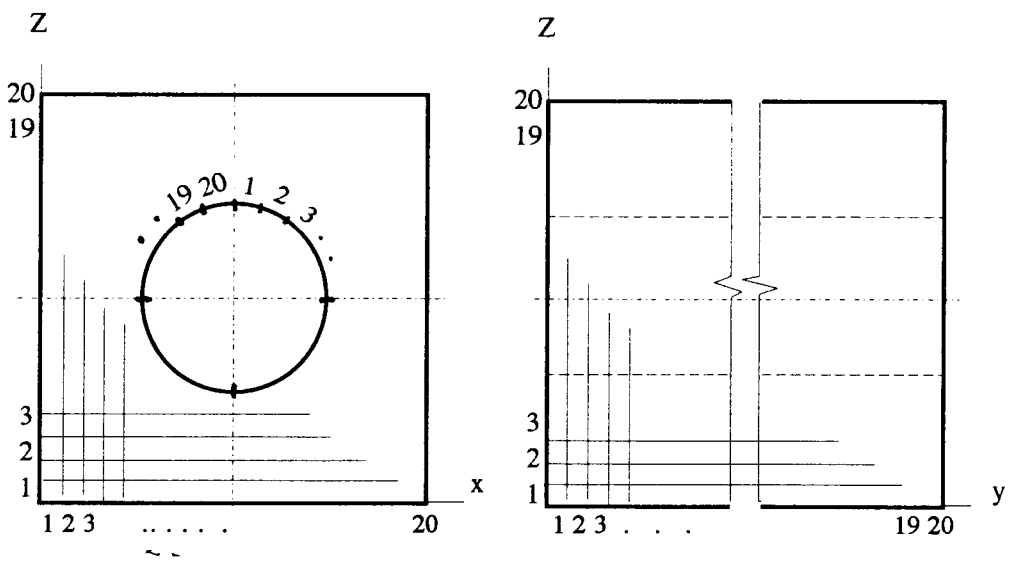


Figure 4. Numerical model configuration

3.1 Algorithm of MCHO3D

Steps involved in the code are listed below :

1. Define initial conditions. First, read geometric parameters (X, Y, Z, D), emissivity and specularity of wall surfaces and optical thickness of medium. The enclosure surfaces, pipe and medium are assumed to have uniform radiative surface properties which are specified by the user ⟨1⟩ [1].

2. N bundles are emitted from wall surface 1.

3. Determine the initial direction of bundle from the source. The surfaces of the enclosure are assumed to be gray, diffusely reflecting and emitting walls, so equations (10), and (11) apply

$$\theta = \sin^{-1}(R_1)^{1/2}$$
$$\phi = 2\pi R_2 \tag{34}$$

where R_1 and R_2 are random numbers between 0.0 and 1.0 ⟨3⟩ .

4. Determine path length, s. If radiative energy travels through a medium, then any incident beam will be attenuated by absorbing and scattering. In terms of

[1] ⟨ ⟩ refers to the corresponding block in flow chart (figure 7)

optical thickness the path length, s, in equation (27) is given by

$$s = -\frac{1}{\tau} \ln R \tag{35}$$

The bundle may be absorbed by the medium before it travels the whole distance, s ⟨4⟩.

5. Determine whether or not the bundle impacts the pipe. From figure 5, a bundle with direction, θ, and path length, s, is emitted from point x.

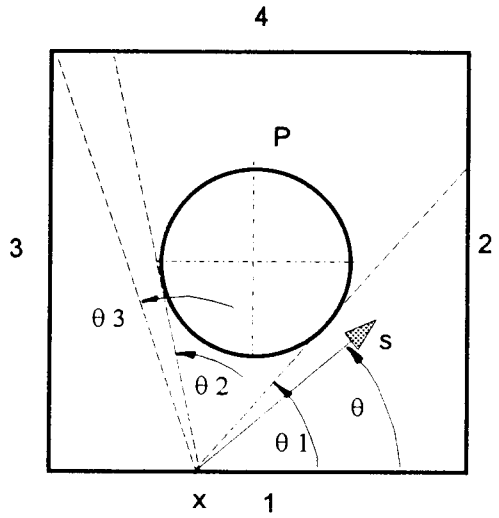


Figure 5. Trajectory of bundle

If θ is less than θ_1 the bundle travels toward wall 2; if the emission angle θ exceeds θ_1, and is less than θ_2 the bundle travels toward the pipe; and if path length s is large enough the bundle will reach either the walls or pipe. Once the impacted wall has been determined, the location of impact is determined by

geometry. If another random number, R_ϵ, is less than the emissivity the bundle will be absorbed at the impacted wall location. At this point the process is repeated $\langle 5, 6 \rangle$.

6. If random number R_ϵ is larger than the emissivity the bundle will be reflected at the impacted point. Figure 6 shows the reflection mode on the wall surface. The patterns of reflection are determined by comparing random number $R_{Reflection}$ with the surface specularity. If $R_{Reflection}$ is less than the surface specularity, the bundle is reflected speculary (reflected angle is equal to incident angle, $\theta_i = \theta_e$).

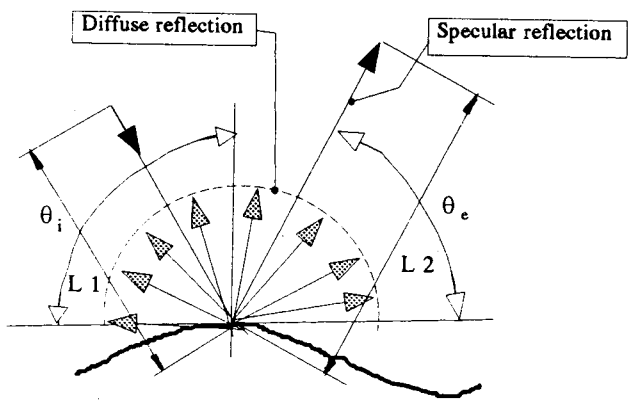


Figure 6. Reflection mode on the wall surface

Otherwise the bundle is reflected diffusely where the diffuse reflection angle will be specified by

$$\theta = \sin^{-1}(R_3)^{1/2} \qquad \phi = 2\pi R_4 \tag{36}$$

where R_3 and R_4 are random numbers between 0.0 and 1.0. In these specular and diffuse reflection cases a new path length, S_{new} , is determined

$$s_{new} = L_2 = s_{old} - L_1 \tag{37}$$

where s_{old} is the s determined in step 4 using equation (35). With the new emission location and angle selected, the procedure is repeated until the bundle is absorbed by either the walls or the pipe $\langle 8,9,10,11,12 \rangle$.

7. If the path length in a given direction is less than the length necessary to impact a surface, the bundle will be absorbed at distance, s. To satisfy radiative equilibrium, a bundle which has equal energy with the bundle absorbed is then emitted from the same point.

The energy spontaneously emitted by an isothermal volume element and the temperature can be obtained knowing the number of bundles absorbed and emitted, so that equation (33) becomes

$$Q_{\Delta V} = 4\,\tau\,\sigma\,T_{dV,P}^4\,dV = (SN_{\Delta V})_p\,\omega = \frac{(SN_{\Delta V})_P}{N} Q_1 \tag{38}$$

or

$$T_{dV} = [\frac{\omega (SN_{dV})_P}{4\tau\sigma dV}]^{1/4} \tag{39}$$

If τ depends on local temperature T_{dV} , an iteration is required. In this work τ is assumed uniform $\langle 15,16 \rangle$. The processes of absorption and emission are

continued until the bundle is absorbed by either the walls or the pipe.

8. Determine a new direction from the medium using

$$\theta = \cos^{-1}(1 - 2R_\theta), \quad \phi = 2\pi R_\phi \tag{40}$$

and also determine a new path length, s, using equation (35) ⟨17, 18⟩.

9. A new bundle is emitted, and the process is repeated until all N bundles have been emitted.

10. Output information is calculated. From equation (30) the dimensionless radiative heat flux reabsorbed at a sub element of wall 1 is determined according to

$$\frac{q_1}{\sigma T_1^4} = \frac{\dfrac{(SN_1)_p}{(\Delta x\, \Delta y)_p}}{\dfrac{N_{total}}{A_1}} \tag{41}$$

Similarly for the other walls we have

$$\frac{q_i}{\sigma T_i^4} = \frac{\dfrac{(SN_i)_p}{(\Delta A)_p}}{\dfrac{N_{total}}{A_1}} \tag{42}$$

where i refers to surface 2,3,4,5,6 or the pipe,P. The temperature at the center of each volume element is found from equation (39) as

$$\Phi_{\Delta V,g,P} = \frac{T_{\Delta V,g,P}}{T_1} = \left[\frac{\omega\,(SN_{\Delta V})_{g,P}}{4\tau\,\sigma\,\Delta V\,T_1^4}\right]^{1/4} = \left[\frac{(SN_{\Delta V})_{g,P}}{4\tau\,N\,\Delta V}\right]^{1/4} \tag{43}$$

and, finally, the dimensionless emissive power in the medium is given by

$$\varphi_p = \frac{(SN_{\Delta V})_{g,P}}{4\tau\,N\,\Delta V} \tag{44}$$

The flow chart for this program sequence is shown in figure 7.

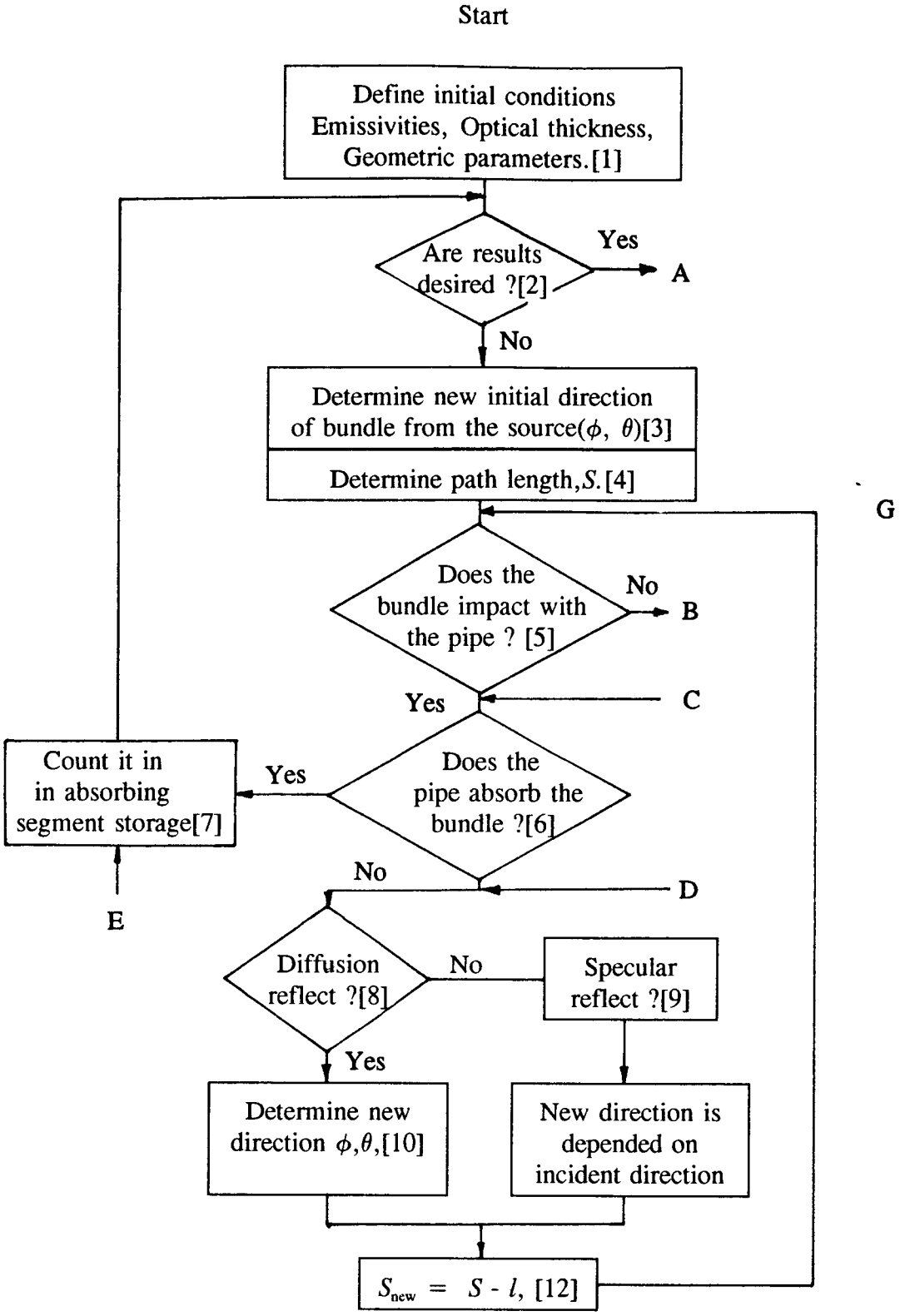


Figure 7. Flow chart of MCHO3D

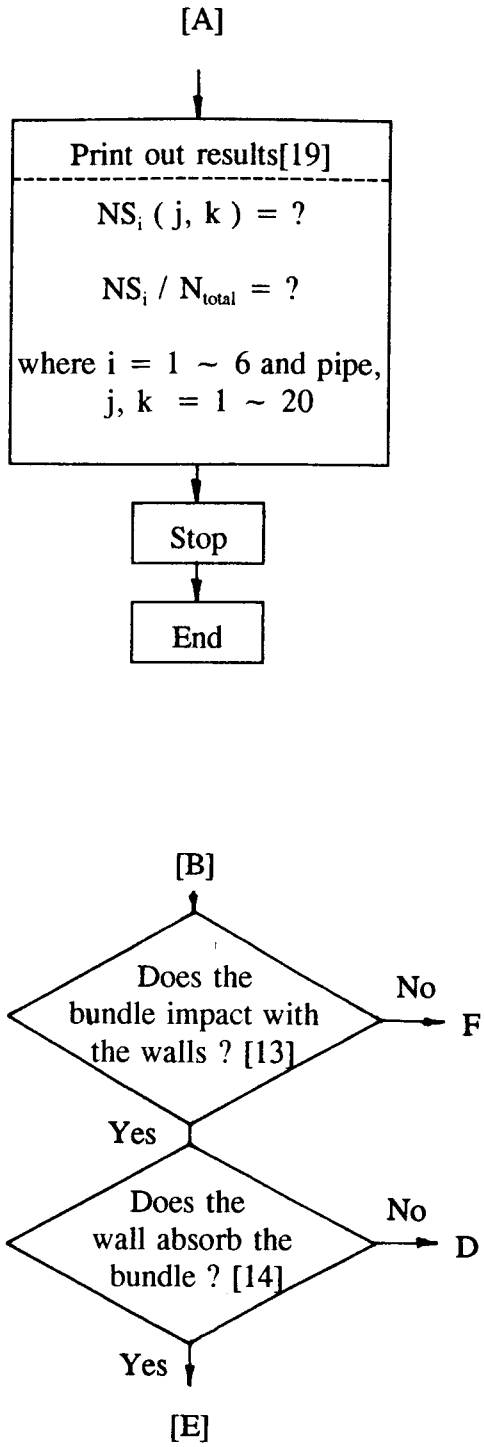


Figure 7. (Continued)

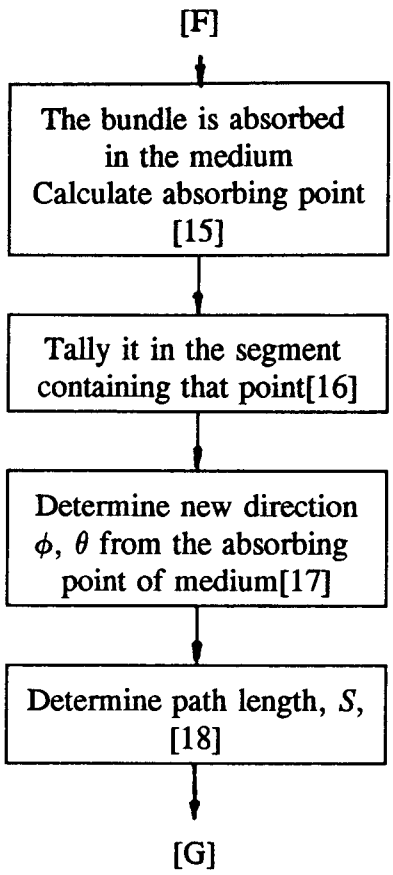


Figure 7. (Continued)

CHAPTER 4

MODEL PARAMETERS

The parameters which were used in each of the cases investigated are listed in table 1.

First, to show the validity of the MCHO3D Monte Carlo code, simple problems that have been analyzed by investigators using different methods were selected for comparison.

The first problem to be analyzed was for one-dimensional parallel plates separated by a gray medium. The second was that of a two-dimensional enclosure containing a gray medium. These cases were then been extended to a three-dimensional case with a cylinder running through the enclosure.

Three geometric parameters (dimensions of the enclosure, and size of the pipe) were varied for specific values of optical thickness of the medium and for wall conditions.

Boundaries of the square duct and circular cylinder were considered black and very cold except for the bottom surface which was a uniform-heat-flux emitting surface. To simplify the simulation the participating medium was considered to be an isothermal, absorbing, emitting, and isotropically scattering gray medium. Optical thickness values were varied from 0 to 10.0.

Figure 1, showing geometric parameters, is included again as figure 8 to assist the reader.

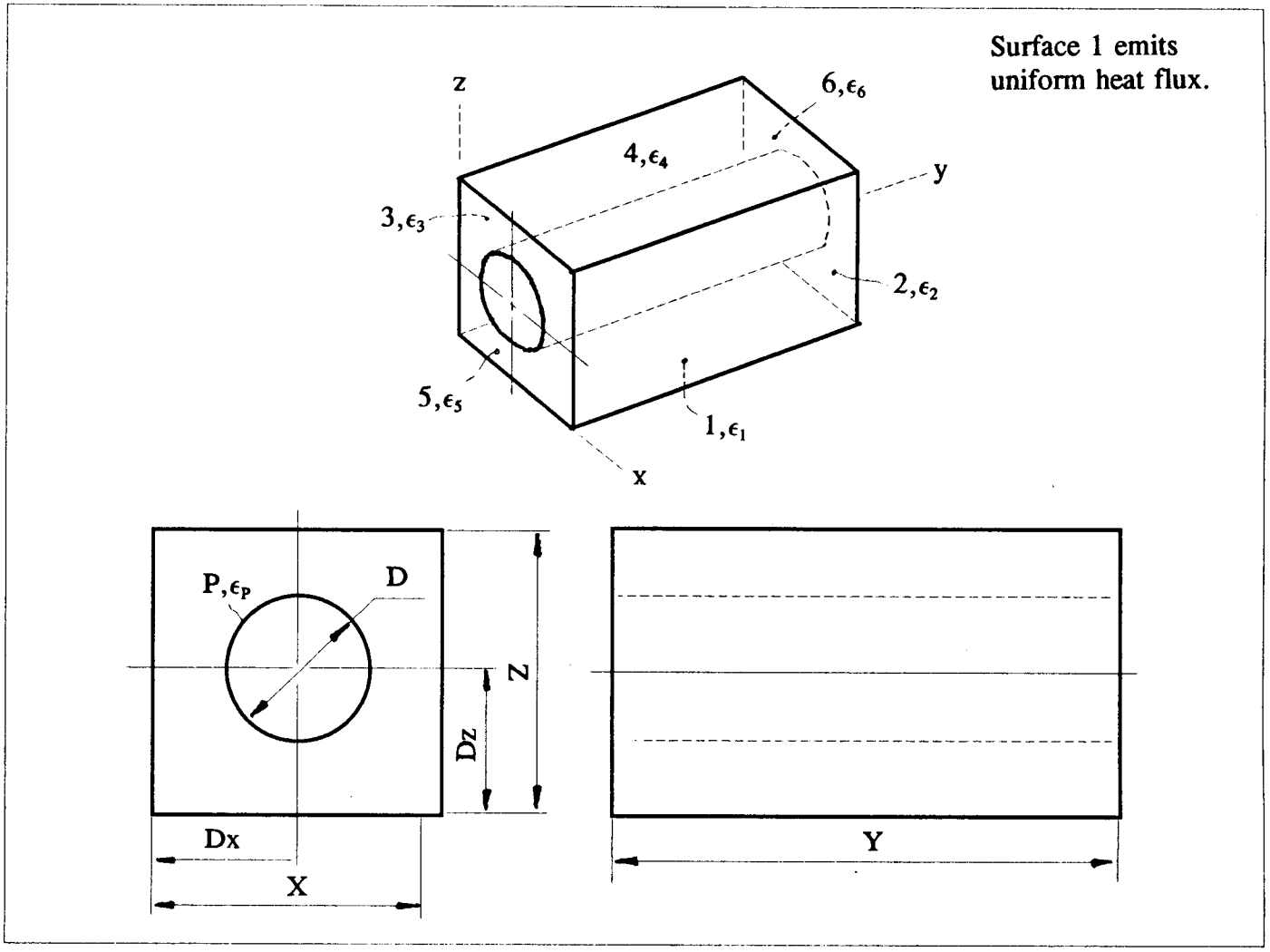


Figure 8. Geometrical configuration.

Table 1. Model parameters.

Case	Geometric shape			$\epsilon_{1-6,P}$	τ
One - D	Z = 1.0, X/Z = Y/Z = 200.0 D = 0.0			1.0	0.5
					2.0
					10.0
Two - D	X = 10.0, Z/X = 1.0, Y/X = 200.0			1.0	1.0
Case 1	X = 10.0 Z/X = 1.0 D/X =0.4 Dx/X =0.5	**Dz/X**	**Y/X**	1.0	<< 1
		0.2	0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 10.0, 15.0, 20.0		
		0.4			
		0.5			
		0.6			
		0.8			
Case 2	X = 10.0 Z/X = 1.0 Dx/X =0.5 Dz/X =0.5	**D/X**	0.1, 2.0, 3.0, 4.0, 5.0, 10.0, 15.0, 20.0	1.0	<< 1
		0.2			
		0.3			
		0.5			
		0.8			
		1.0			
Case 3	X = 10.0 Z/X = 1.0 D/X = 0.4	Dz/X = 0.5	0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 10.0, 15.0, 20.0	1.0	<< 1
					0.5
					1.0
					3.0
					5.0
					10.0
Case 4	X = 10.0 Z/X = 1.0 D/X = 0.4	Dz/X = 0.5	3.0	1.0	//

CHAPTER 5

RESULTS AND DISCUSSION

A numerical investigation involving the effects of radiation in a square duct with a centered, circular pipe has been conducted. The situations considered in this study involve two different parameters, geometrical shape factors and optical thickness. The cases evaluated include a variety of combinations of these parameters. Numerical results are presented graphically.

5.1. Comparison with other methods

The purpose of this section is to describe how the MCHO3D Monte Carlo code, which was developed for a three-dimensional case, compares to known one- and two-dimensional results.

Considering, first, a one-dimensional enclosure with parallel black ($\epsilon_{1,2} = 1.0$) plates separated by an absorbing and emitting gray medium that is in radiative equilibrium, i.e. radiation is the only mode of heat transfer, the universal function for nondimensional radiation heat flux is

$$\Psi_b(\tau) = \frac{q}{n^2 \sigma (T_1^4 - T_2^4)} \tag{45}$$

or

$$\Psi_b(\tau) = 1 - 2\int_0^{\tau_L} \Phi_b(\tau') E_2(\tau')\, d\tau' \tag{46}$$

and nondimensional emissive power or temperature is

$$\Phi_b(\tau) = \frac{T^4(\tau) - T_2^4}{T_1^4 - T_2^4} \tag{47}$$

or

$$\Phi_b(\tau) = \frac{1}{2}\left[E_2(\tau) + \int_0^{\tau_L} \Phi_b(\tau') E_1(|\tau - \tau'|) d\tau'\right] \tag{48}$$

where τ' is a dummy variable [7,26]. The numerical solution to these two equations (46) and (48) was first given by Heaslet and Warming [26]. The solid lines in figures 9 and 10 include the results of numerically solving equations (46) and (48) [26].

To simulate one-dimensional geometry, since MCHO3D was developed for three-dimensions, the geometric ratios were taken to be X/Z = 200.0, Y/Z = 200.0 and D/Z = 0.0001. One emitting source at the center of the bottom wall was used. Had the emitting source points been selected randomly along the x axis it would not have been a one-dimensional case. To examine the validity of choosing these parameters, the numbers of bundles absorbed at walls 2, 3, 5, and 6 were counted. Characteristically fewer than two bundles out of a thousand were absorbed in each case, thus the one-dimensional results are valid. For the one-dimensional case, equations (42) and (44) become

$$\frac{q_4}{q_1} = \frac{SN_4}{N_{total}} \tag{49}$$

and

$$\varphi_P = \frac{\epsilon (SN_{\Delta Z})_P}{4\tau\, \Delta Z\, N_{total}} \tag{50}$$

respectively, and were used to calculate the values which are shown as individual results in figures 9 and 10, with good agreement achieved. The scattering in Monte Carlo results for emissive power distribution evaluated at the lower values of optical thickness is a statistical phenomenon. If the number of bundles were increased less scatter would be obtained.

The next comparison was with two-dimensional enclosure results of a study conducted by Kim and Lee [25]. They solved isotropic and anisotropic scattering cases using the S-N discrete ordinate method. Other results by Thynell and Özisik [27], who achieved a solution for the isotropic scattering case using the Galerkin method [28] were also used for comparison. These two studies were performed with various values of the albedo ($\omega = \sigma_S / \beta$). In the present work the value of the albedo was chosen as $\omega = 1.0$. The incident radiation in the medium is the total intensity impinging on a point from all sides defined by the following equation (51)

$$G_\lambda = \int_0^{4\pi} I_\lambda(\bar{r})\, d\omega \tag{51}$$

Boundary conditions in both cases include the bottom surface emitting

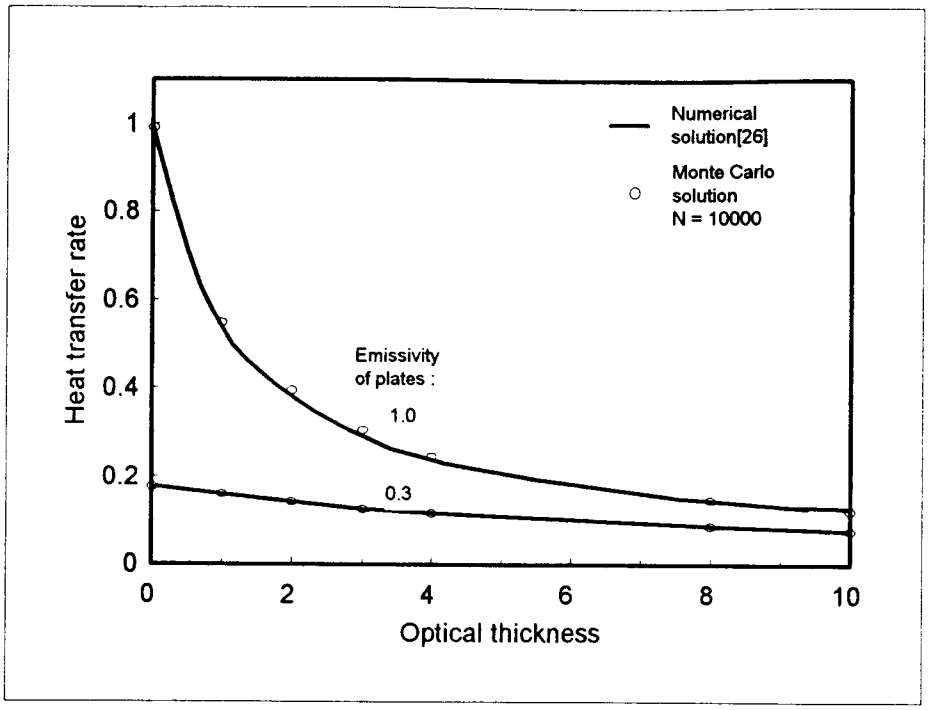


Figure 9. Heat transfer between infinite parallel gray plates containing a gray medium

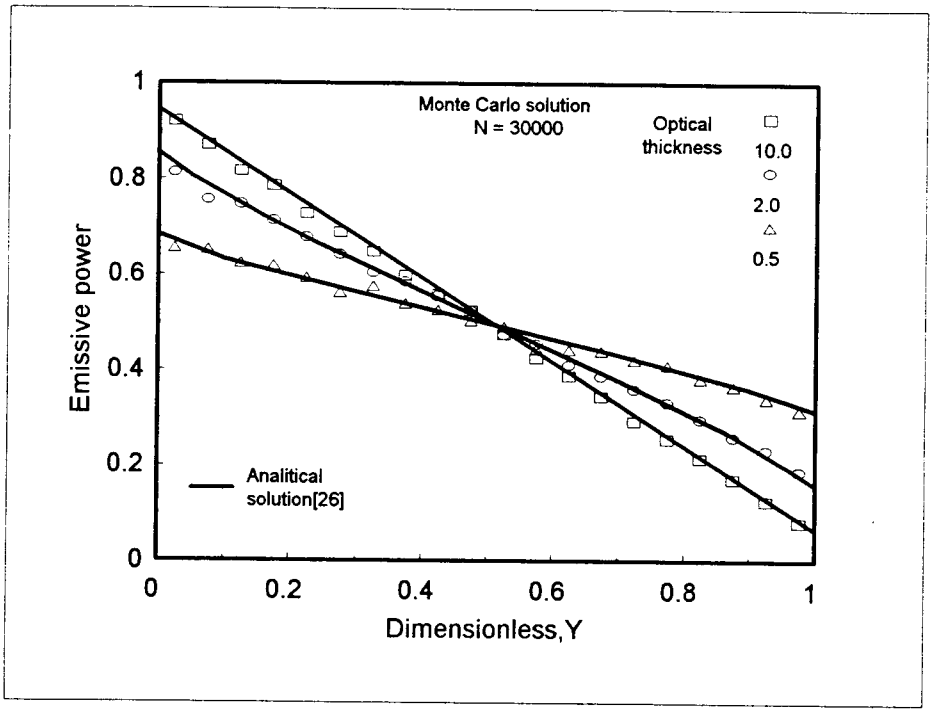


Figure 10. Distribution of emissive power in gray medium with no source

isotropically as a constant flux surface. The remaining three wall surfaces are considered to contain no external energy sources and there was no energy source in the medium. To match geometric similarity the following values were used: Z/X = 1.0, Y/X = 200.0, and D/X = 0.0001. To establish the base as a uniform energy surface, a line source along x at y = Y/2 was used. Different grids were used in each case. In MCHO3D the simulation model was subdivided into 20×20 grid. In the S-N discrete-ordinate method the enclosure was divided into a 26×26 grid. The Galerkin method included seven values (z/X = 0.0, 0.1, 0.2, 0.3, 0.5, 0.7,1.0). Figure 11 is a comparison of the incident radiation distributions of these three methods and shows excellent agreement between them. These two

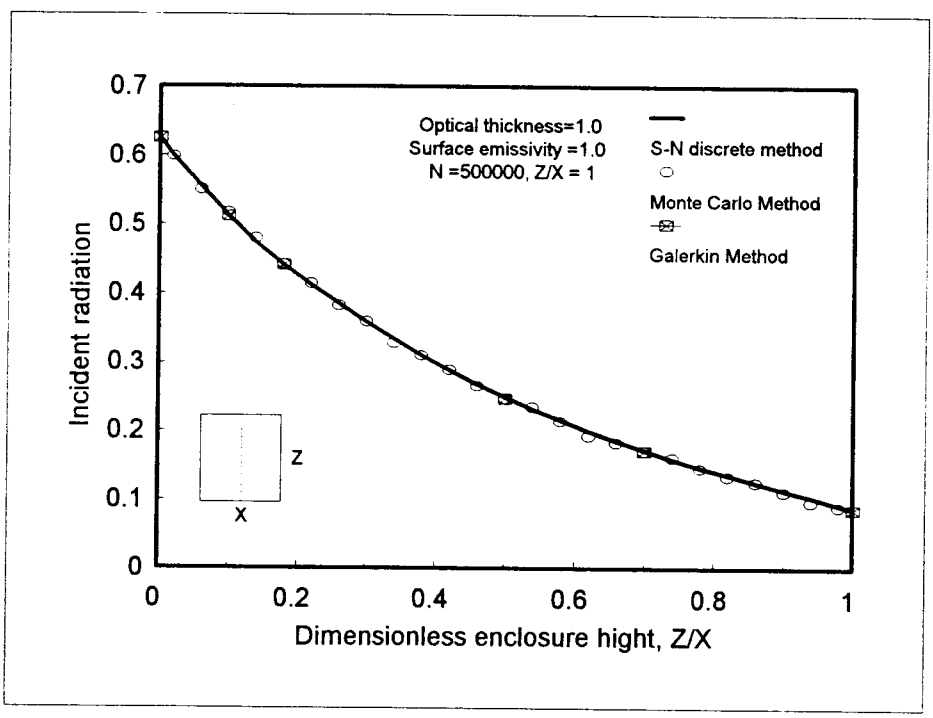


Figure 11. Incident radiation of medium along the vertical center line at x = X / 2.

comparisons demonstrate that the MCHO3D code is a valid method for evaluating three- or multi-dimensional cases.

5.2. Geometric Variations

In cases 1 and 2, heat transfer rates and the distribution of radiative heat flux were examined for a range of geometric shapes, locations of the circular cylinder along the vertical center line, and cylinder diameter. Since the walls are black in this problem, there is no reflected radiation from surfaces, and because the medium is isotropically scattering, the fractional radiative energy in any particular direction incident on surfaces from the entire medium remains unchanged. Also for the case with the optical thickness approaching zero the space between surfaces can be considered as a vacuum and the resulting radiation heat transfer rates are directly related to their view factors and would yield the exact solution for the wall heat flux. For this case equation (42) becomes

$$\frac{q_i}{q_1} = \frac{SN_i}{N_{total}} \qquad (i=1,2,3,4,5,6,P) \quad (52)$$

Figure 12 shows the dimensionless radiative heat transfer rate from the bottom surface to the pipe as a function of enclosure depth and pipe location. Figure 13 shows the variation of radiative heat transfer rates at each surface. An inspection of figure 12 reveals that for enclosure depths, Y/X , greater than 5, the view factor (or radiation heat transfer rate) remains almost unchanged, i.e. it approaches but

never reaches the values of the corresponding two-dimensional case and these trends seem somewhat independent of the location of the pipe. This figure also shows that the radiation heat transfer rates for the pipe are increased at pipe locations close to the bottom surface. The maximum heat transfer (also maximum $F_{1\text{-}P}$) between the base (surface 1) and the pipe will occur when the pipe is in contact with the base. For the case shown this maximum is 0.475 of the total. Figure 13 shows that transfer rates for each wall surface show only modest change after Y/X=5. The results of a study of Wiebelt and Ruo [31], in which they obtained view factors between a finite right-circular cylinder and a parallel rectangular surface using the contour integration method, show similar trends.

The distributions of radiative heat flux around the pipe are shown in figure 14. These cosine-like heat flux profiles were obtained for a lateral line at y=Y/2. When the pipe is in contact with the base the dimensionless radiative heat flux approaches to 1.0. For each pipe location the maximum radiative heat fluxes are the limiting values for an infinitely long enclosure (the two-dimensional case).

Figure 15 shows the heat flux profiles on both side wall surfaces (2, 3) which are perpendicular to the heated wall (surface 1). The dimensionless radiative heat fluxes approach a value of approximately 0.5 as the vertical location, z , approaches zero. In figure 15 (d) in which the diagonal lines of the enclosure do not intersect the pipe, the dimensionless radiative heat fluxes approach the value of 0.146 as vertical location, z, approaches 1.0 and Y/X approaches infinity. The dimensionless radiative heat flux for an infinitely small element in case 1 can be easily calculated using the crossed-string method [4,7]. It is shown in

Appendix 1 that the radiative heat flux approaches 0.5 when $n \rightarrow \infty$.

Figure 16 shows the heat flux distributions along the center line of the upper wall surface of the enclosure. These figures show clearly the effects of pipe location. The radiative heat flux distributions of figures 15 and 16 show there to be a discontinuity at each corner. This radiative heat flux slip (or jump) is a result of geometry and will disappear when heat conduction is present.

The results for case 2 are shown in figures 17 and 18. In this case it is clear that the radiative heat transfer rate to the pipe will increase as the diameter of the pipe is increased as expected. The effect of enclosure depth shows similar trends as for case 1.

From figure 17 we observe that the maximum radiation heat exchange between wall 1 and the enclosed cylinder reaches a maximum value of 78 percent of the total with the remaining 22 percent transferred to the side walls.

The results of the studies of cases 1 and 2 show that, if the optical thickness of the intervening medium is small ($\tau \ll 1$), the geometric view factor, F_{i-j}, is valid even though boundary conditions way change.

5.3 Optical Thickness Effects

The second part of this study was undertaken to answer the question " What happens when the optical thickness of the intervening medium varies from optically-thin to the optically-thick state ?" In cases 1 and 2 the optical thickness

was very small (effectively zero), thus the attenuation by absorption and scattering was negligible. In cases 3 and 4 an incident beam was attenuated by absorption and scattering while traversing the enclosure. For isotropic scattering in the case of a gray medium in radiative equilibrium, there is no distinction between absorption and scattering. Any energy absorbed at τ must be reemitted isotropically at the same location, i.e., any isotropically scattered energy is simply redirected isotropically.

If a bundle path length is less than the maximum path length the bundle will be absorbed. To satisfy energy equilibrium, a bundle is then reemitted from the same location. The probability that the bundles are absorbed prior to reaching another surface is increased as the optical thickness is increased.

Results of case 3 are shown in figures 19 and 20. Figure 19 shows the effect of optical thickness on dimensionless heat flux to the pipe over a range of with enclosure depth Y/X. Radiation heat transfer rates to the pipe at small values of optical thickness are larger than for large optical thicknesses for all values of enclosure depth, Y/X, since the resistance through the medium is relative small.

Figure 20 shows the variation of radiative heat transfer rates at each wall as a function of optical thickness for various enclosure depths, Y/X. As expected radiation heat transfer rates to each wall decreased as optical thickness increased for all enclosure depths.

In figure 21, radiation heat flux values around the pipe are presented with the optical thickness as the parameter. The total radiation heat transfer rate to the pipe decreased with an increase in optical thickness.

Figure 22 shows the reabsorbing radiation heat-flux distribution at the bottom surface as a function of optical thickness. For parallel plates the distribution would be flat for all optical thicknesses. This figure shows that the effect of side walls was greater for increased optical thickness.

Figure 23 shows the distribution of heat flux at the upper surface of the enclosure. The effect of the pipe is seem to decrease and the heat flux approached zero as the optical thickness increased.

In figure 24 the radiation heat flux distribution along the side walls is also observed to approach zero for large values of optical thickness.

To show the effects of optical thickness for each wall surface and pipe more clearly the distribution of radiative heat flux was plotted in three-dimensions for case 4. Figures 25 through 29 show the distribution of radiative heat flux around the pipe, along walls 2 and 3, wall 4, and walls 5 and 6, respectively. As the optical thickness was increased, the heat flux decreased in all cases except for wall surface 1, the bottom surface.

These results show that radiation heat transfer rates in enclosures filled with an optically thin medium ($\tau \ll 1$) can be accurately predicted using geometric view factors. If, however, the optical thickness of the medium is 0.1 or greater it is necessary to include the effects of participating media in the analysis.

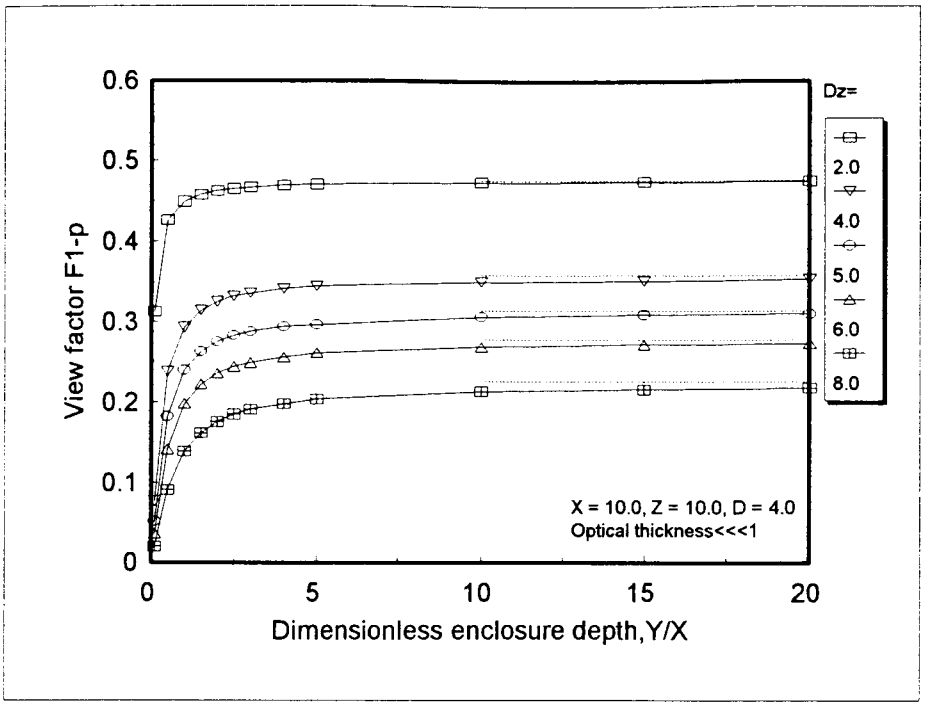
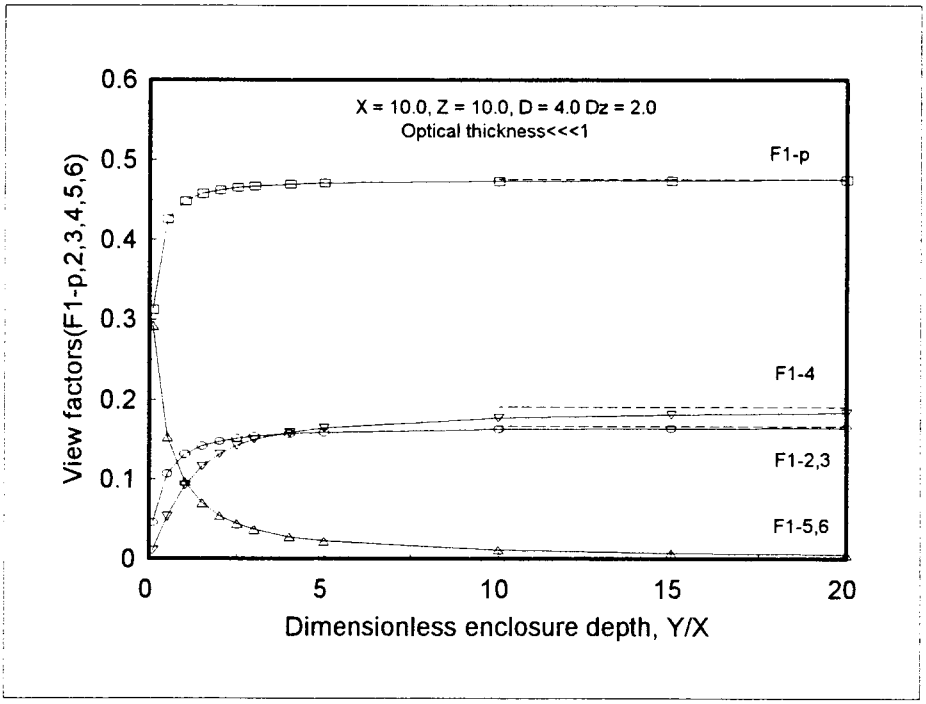
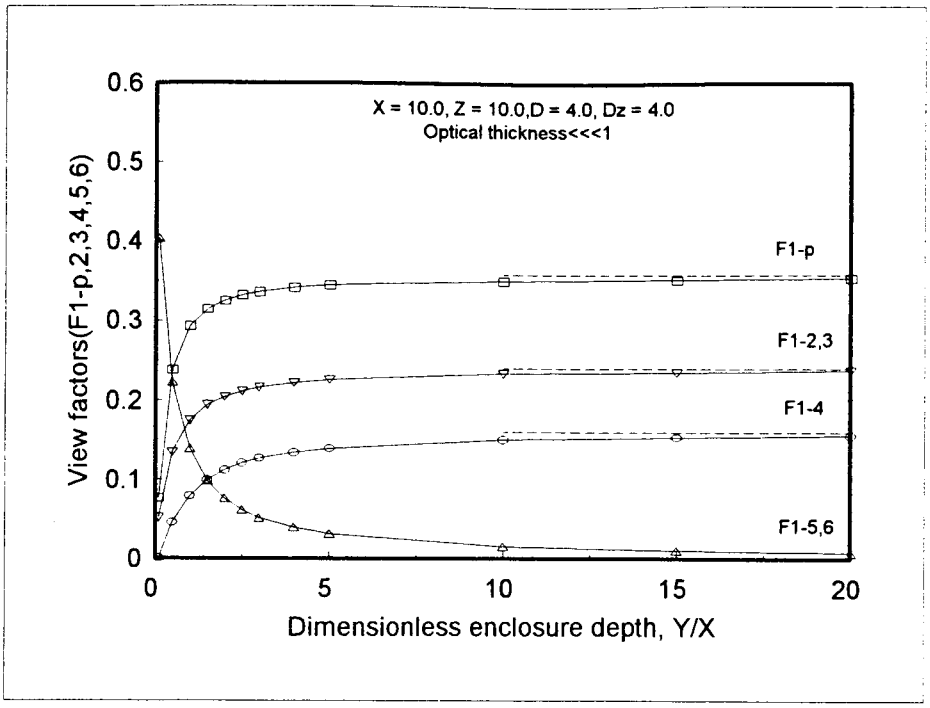


Figure 12. Variation of view factors $F_{1\text{-}P}$ with enclosure depth and pipe location (--- refers to Y/X = ∞)

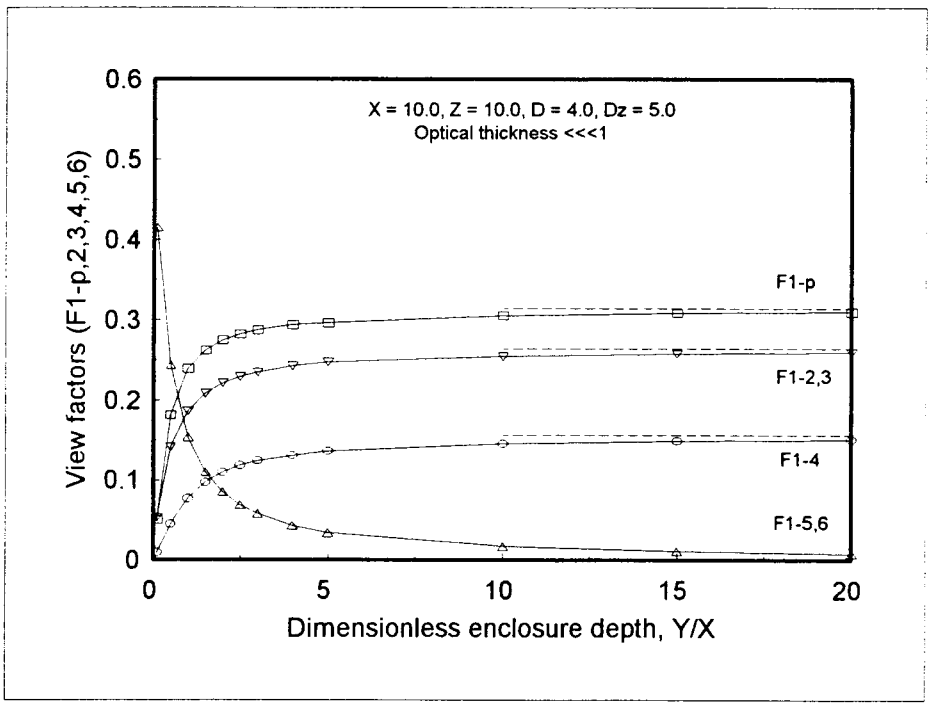


(a) Dz = 2.0

Figure 13. Variation of view factors $F_{1\text{-}j}$ with enclosure depth (--- refers to Y/X = ∞)

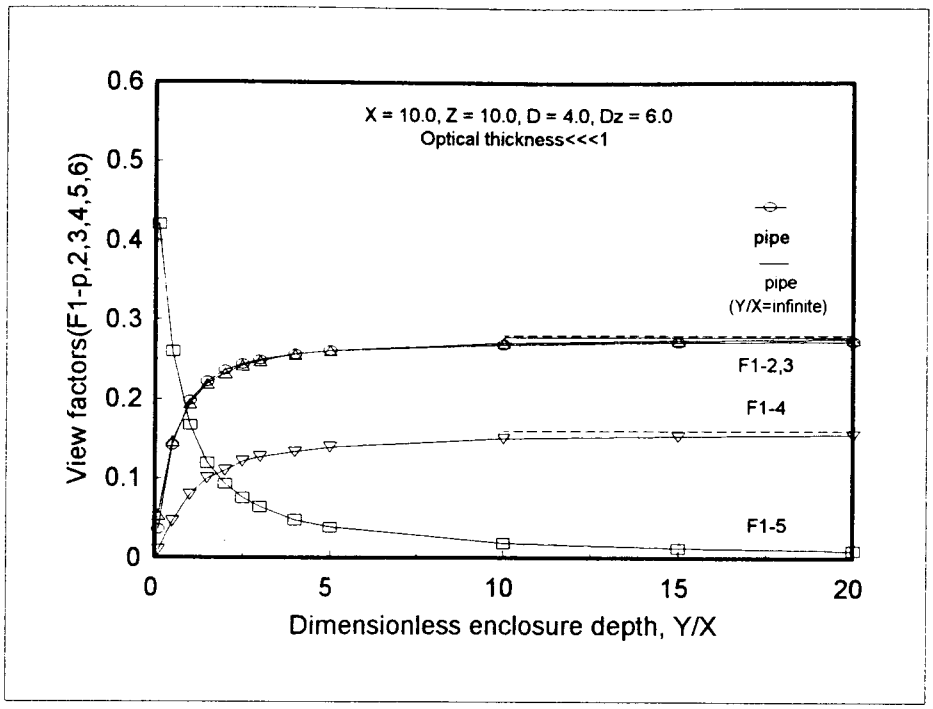


(b) Dz = 4.0

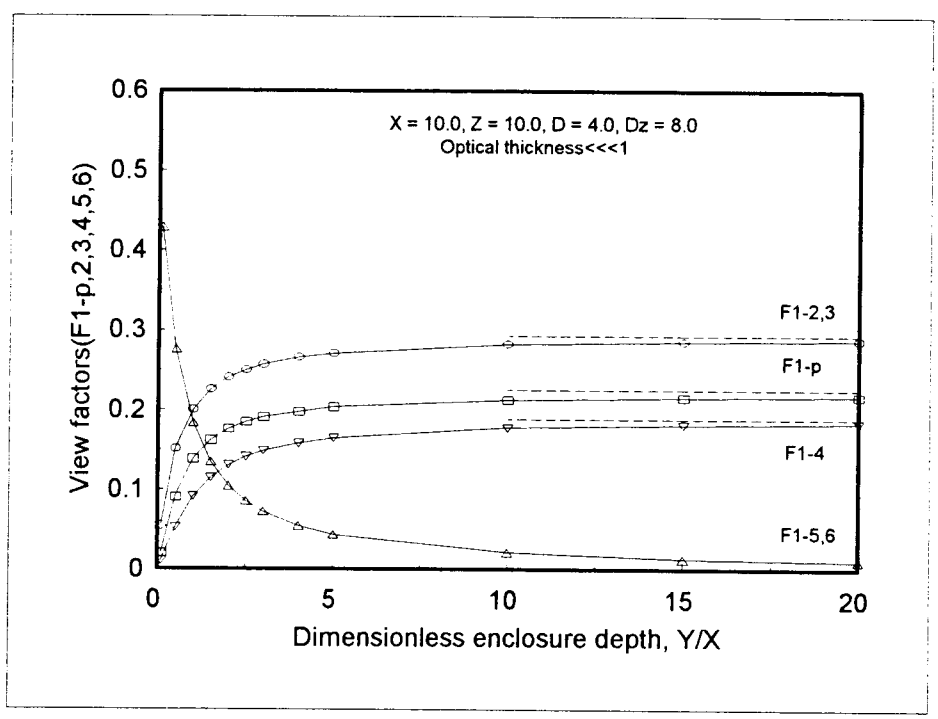


(c) Dz = 5.0

Figure 13. (continued)

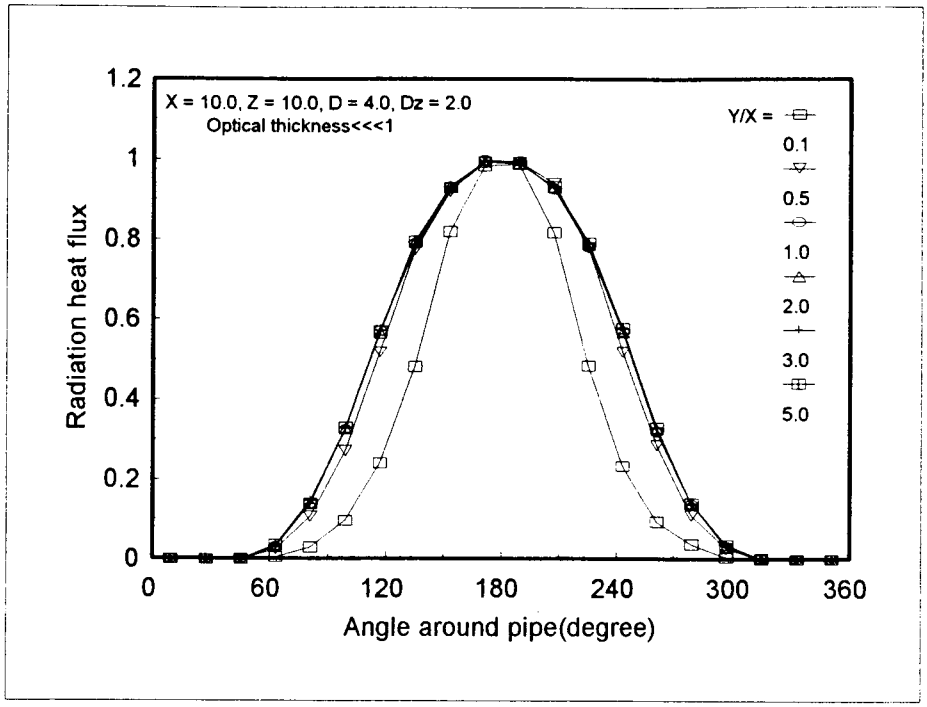


(d) Dz = 6.0

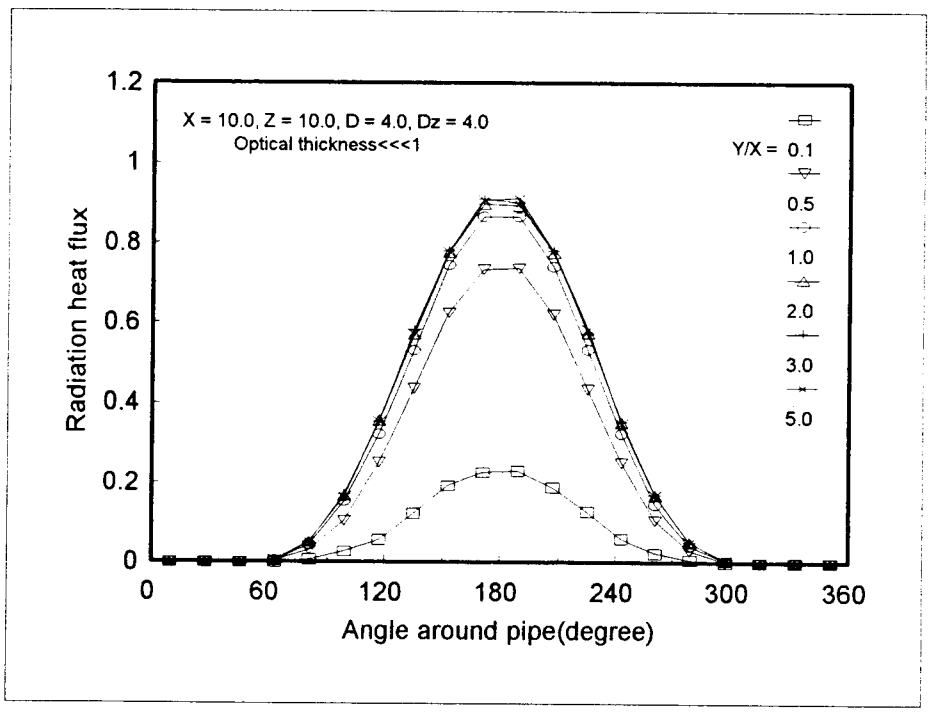


(e) Dz = 8.0

Figure 13. (continued)

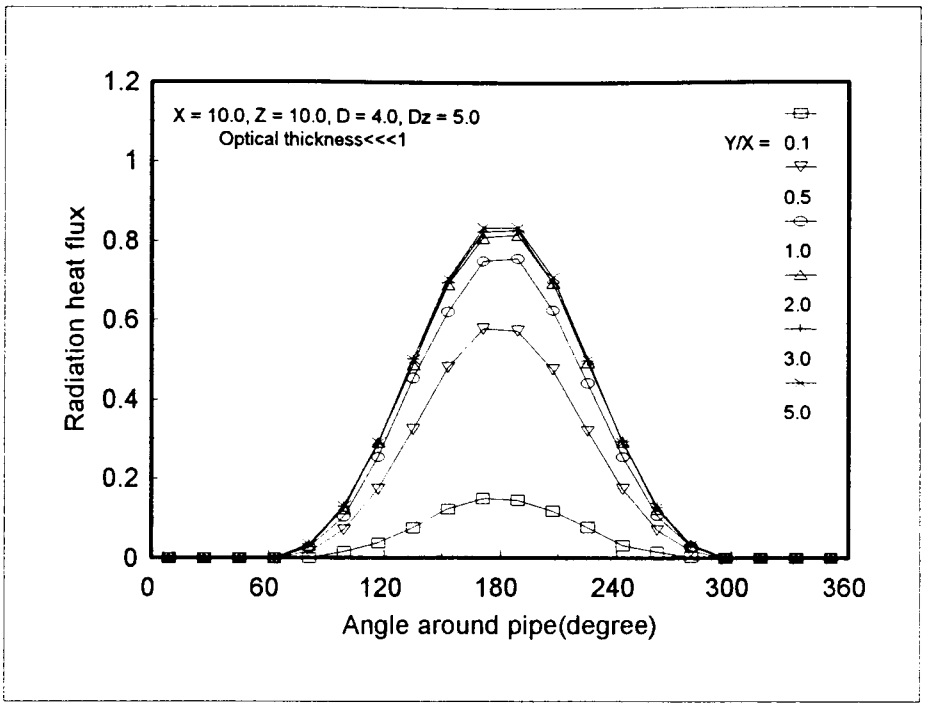


(a) Dz = 2.0

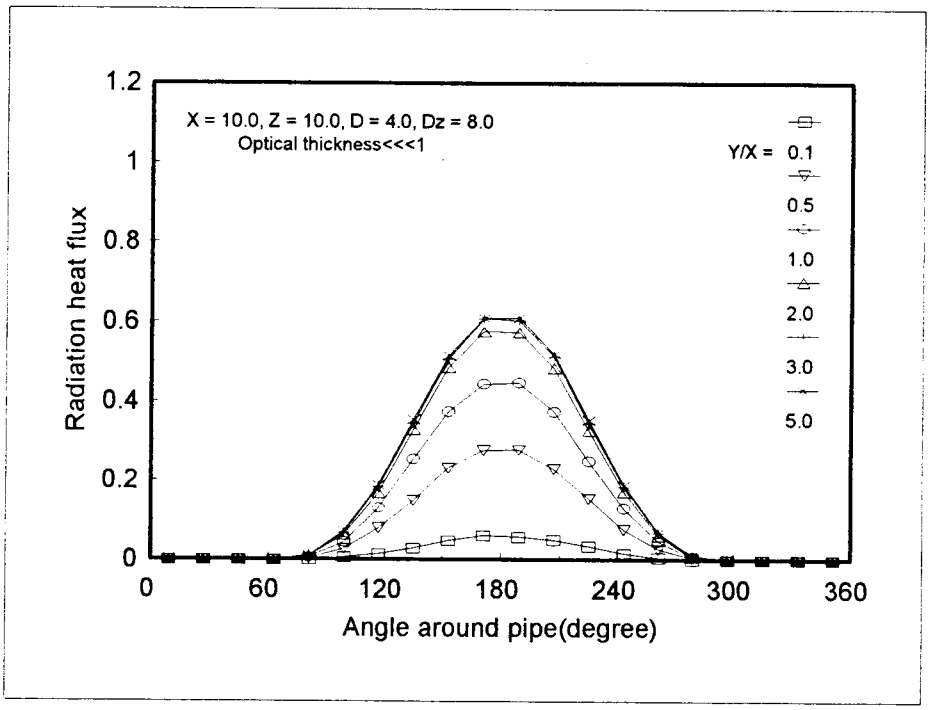


(b) Dz = 4.0

Figure 14. Distribution of radiation heat flux around pipe at y = Y/2 with enclosure depth

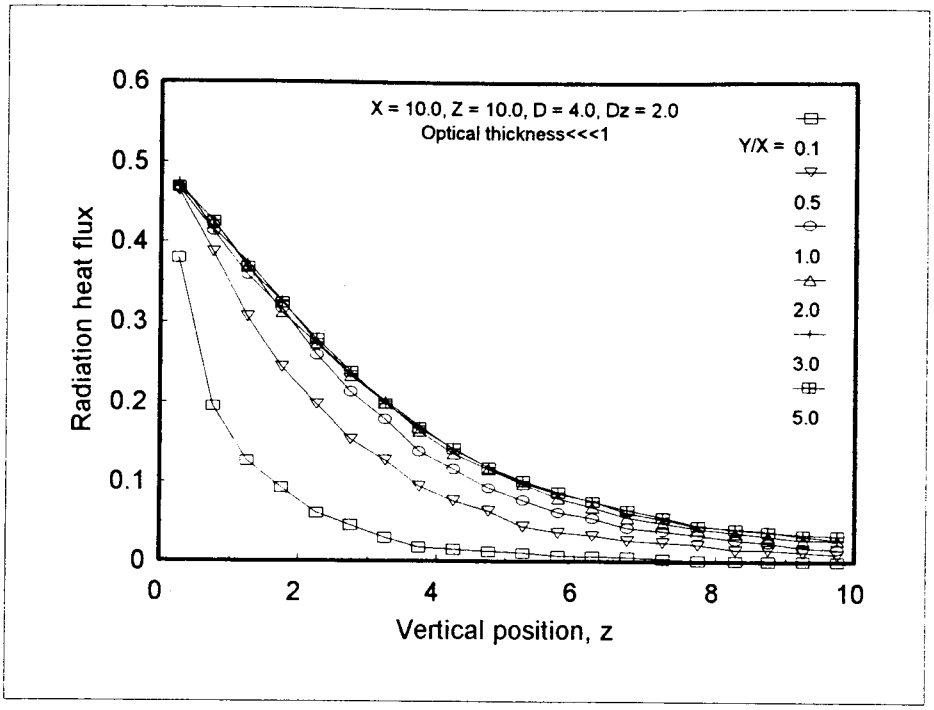


(c) Dz = 5.0

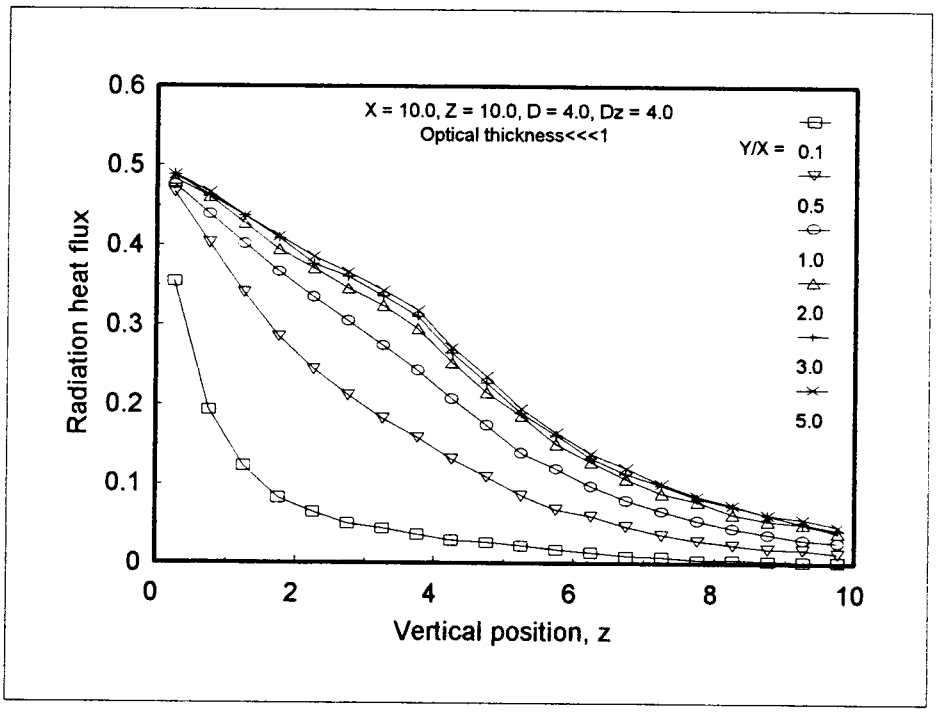


(d) Dz = 8.0

Figure 14 (continued)

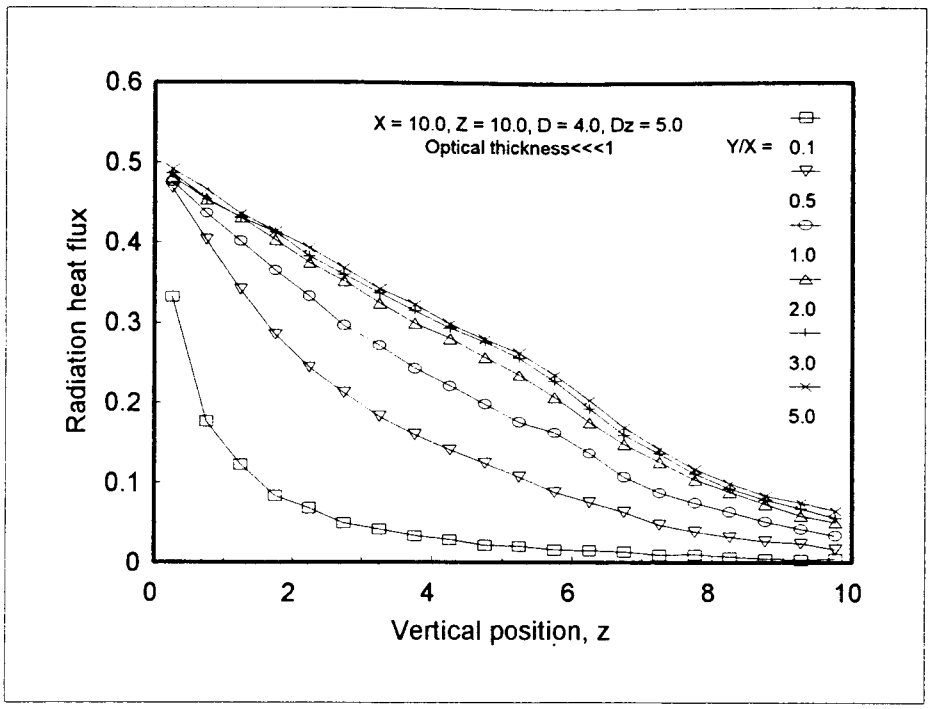


(a) Dz = 2.0

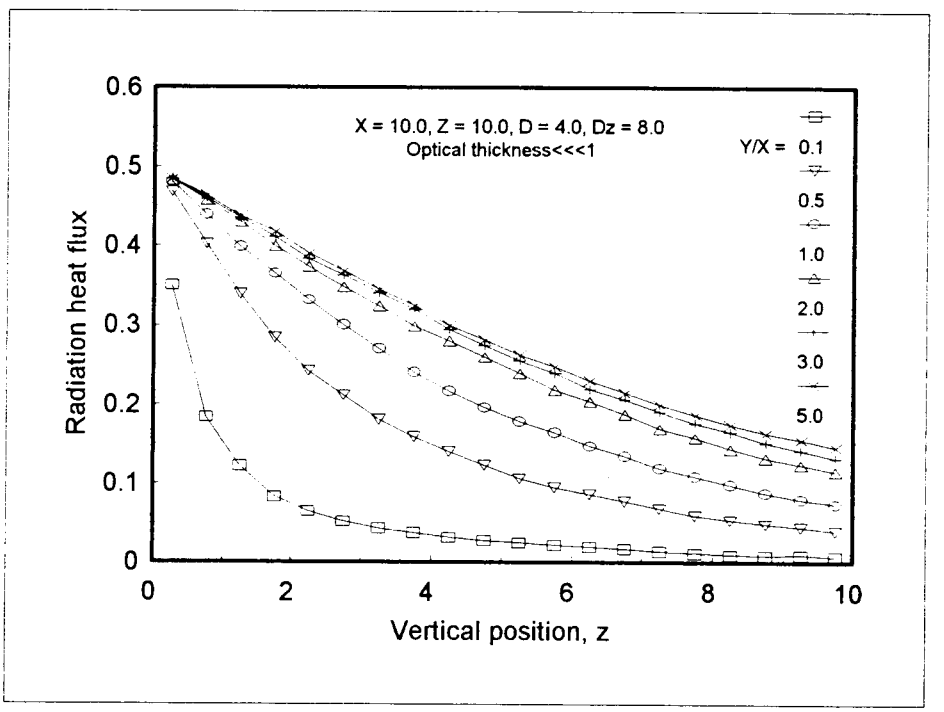


(b) Dz = 4.0

Figure 15. Distribution of radiation heat flux to center line of side walls, y = Y/2

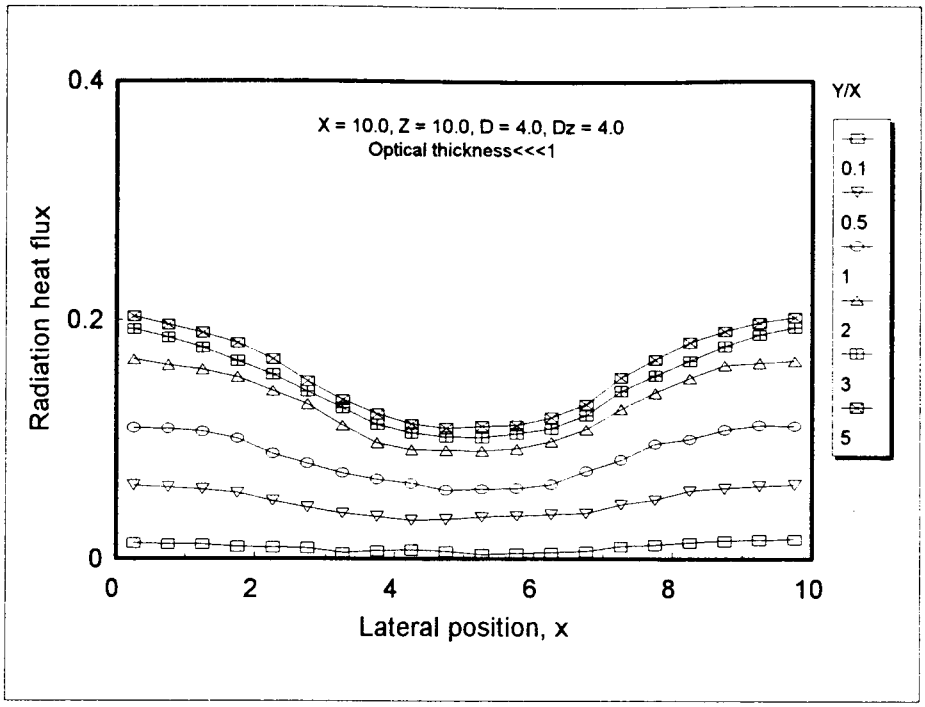


(c) Dz = 5.0

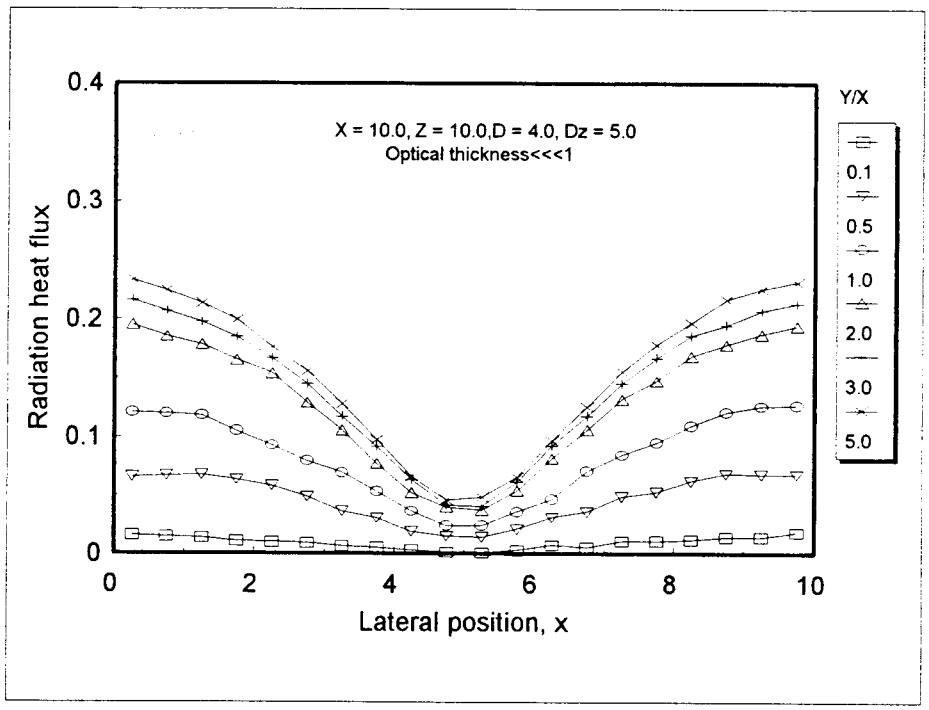


(d) Dz = 8.0

Figure 15. (continued)

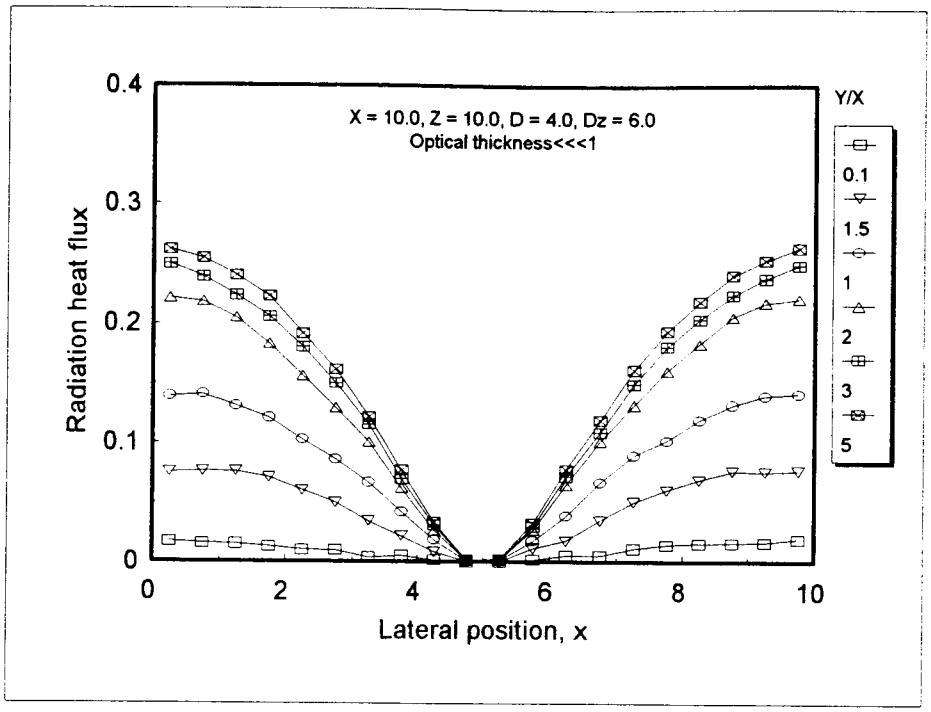


(a) Dz = 4.0

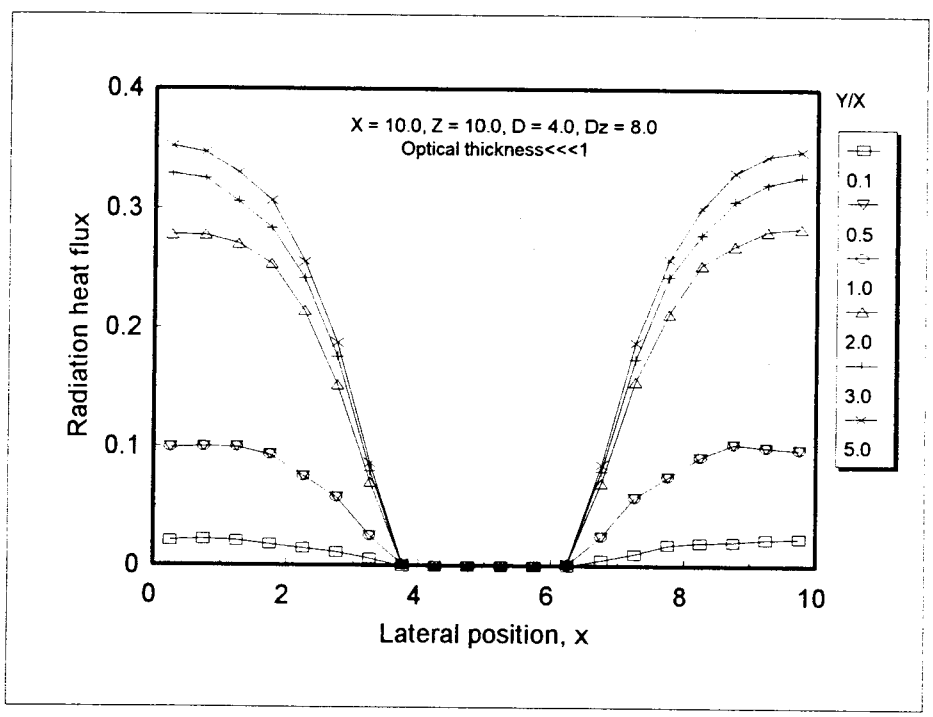


(b) Dz = 5.0

Figure 16. Distribution of radiation heat flux to center line of top surface, y = Y/2



(c) Dz = 6.0



(d) Dz = 8.0

Figure 16. (continued)

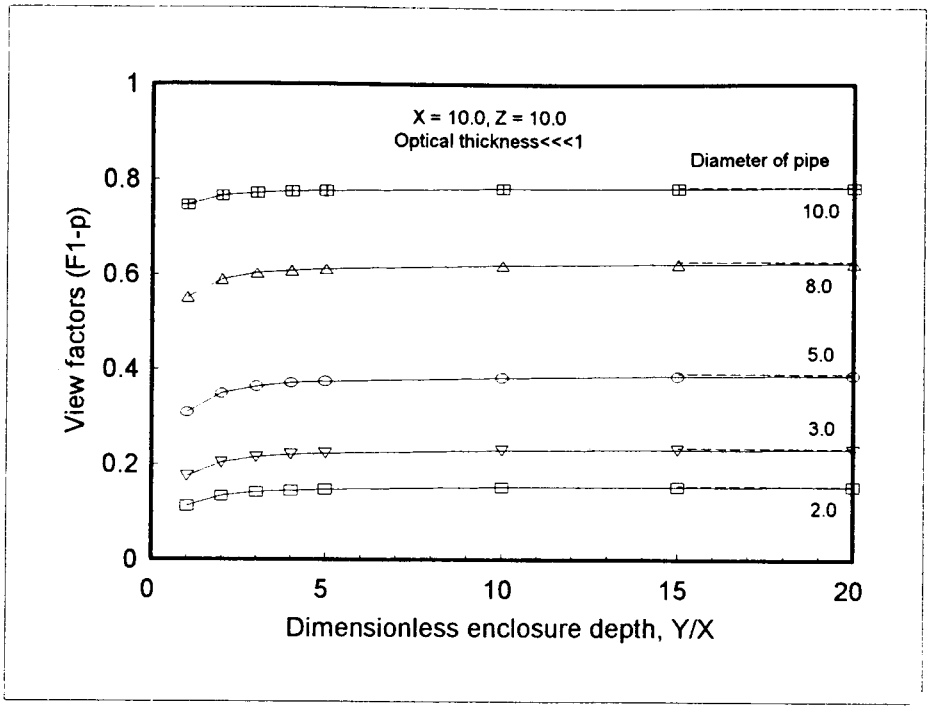
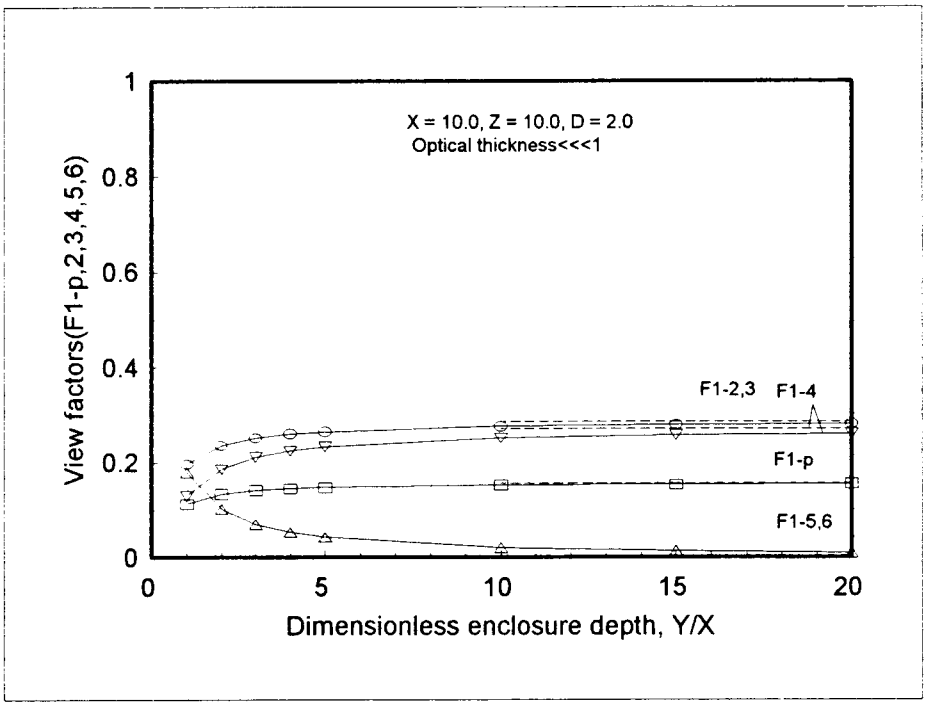
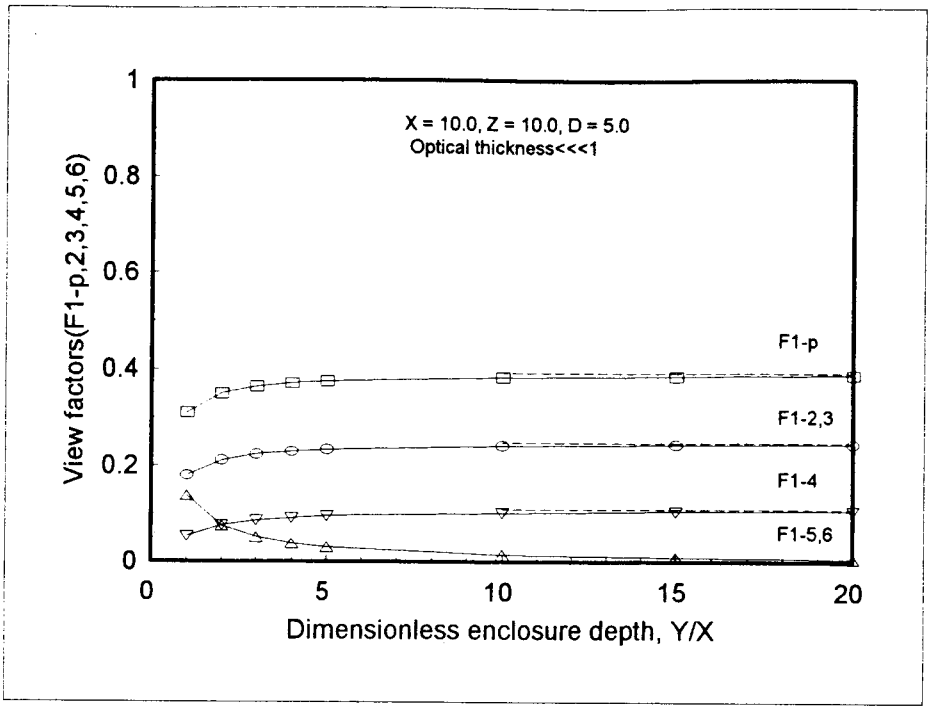


Figure 17. Variation of view factors $F_{1\text{-}P}$ with enclosure depth and pipe diameter (--- refers to Y/X = ∞)

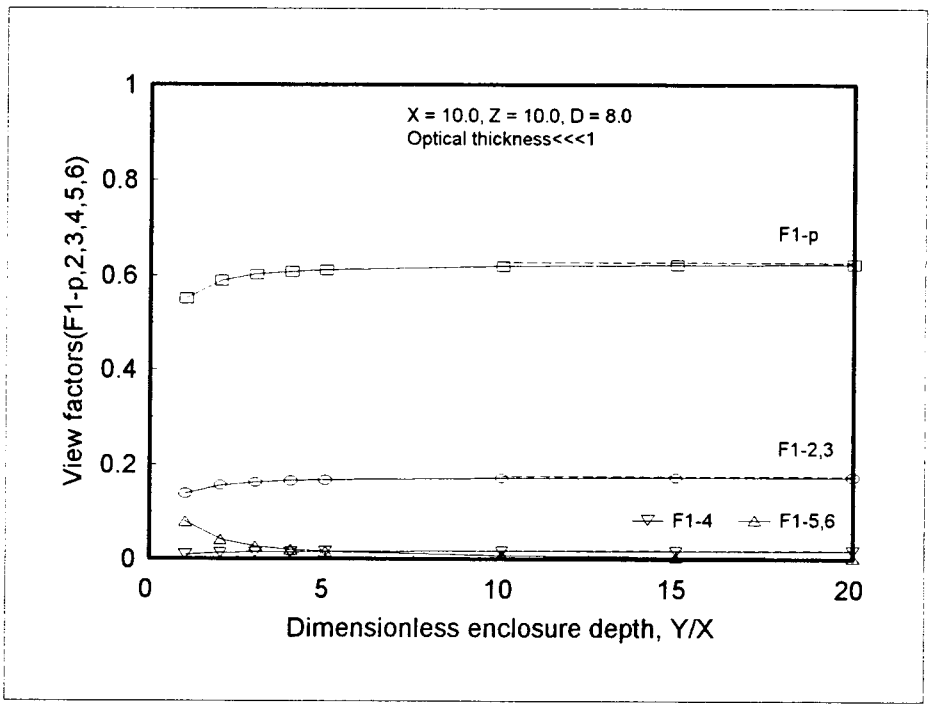


(a) D = 2.0

Figure 18. Variation of view factors $F_{1\text{-}j}$ with enclosure depth (--- refers to Y/X = ∞)

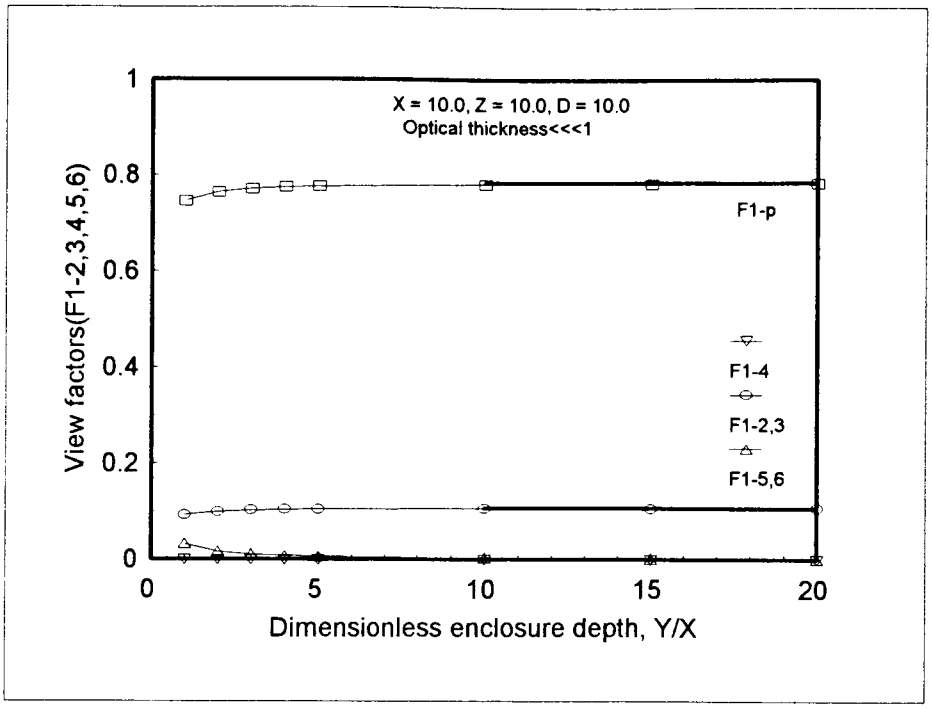


(b) D = 5.0



(c) D = 8.0

Figure 18. (continued)



(d) D = 10.0

Figure 18. (continued)

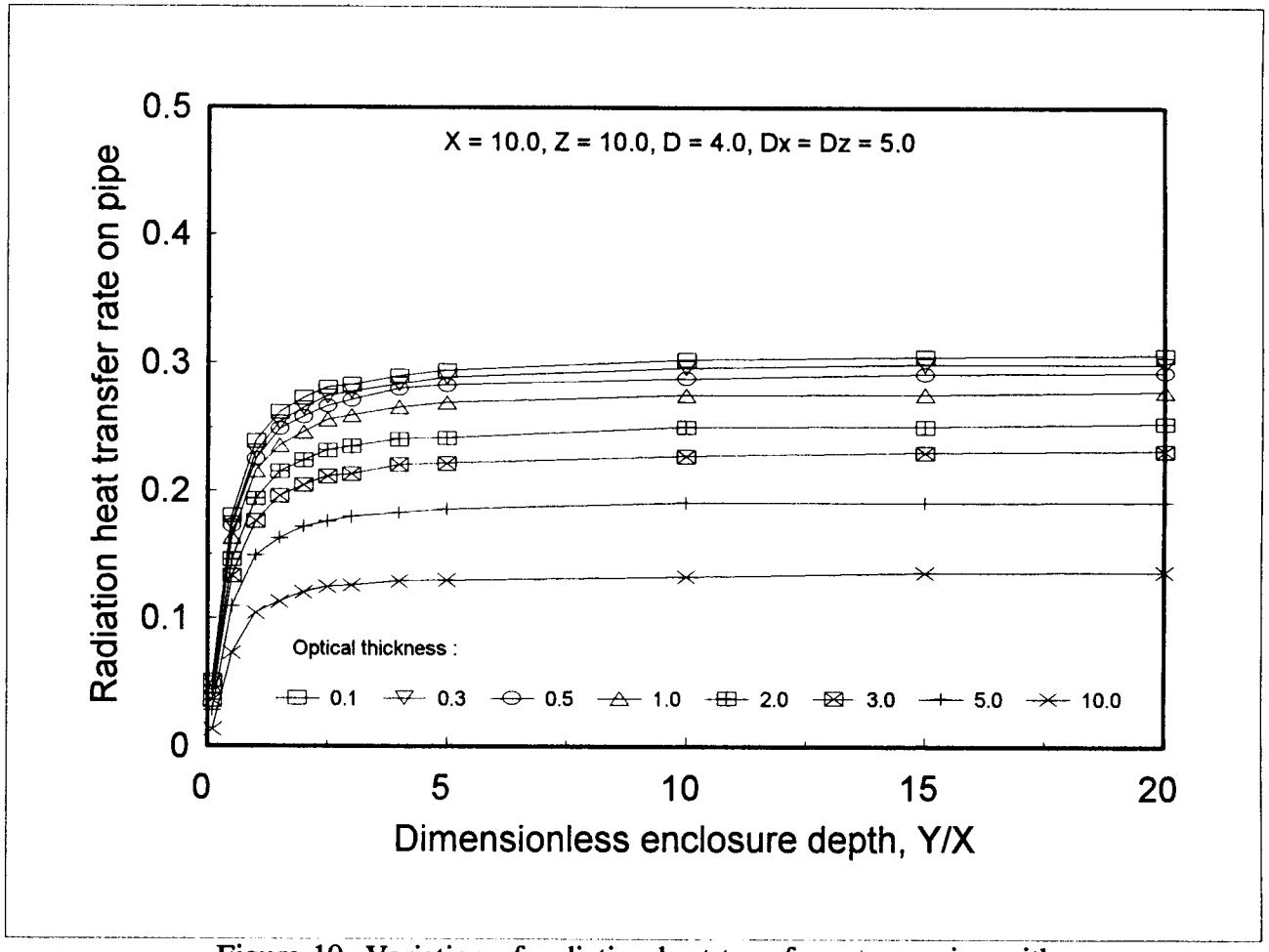
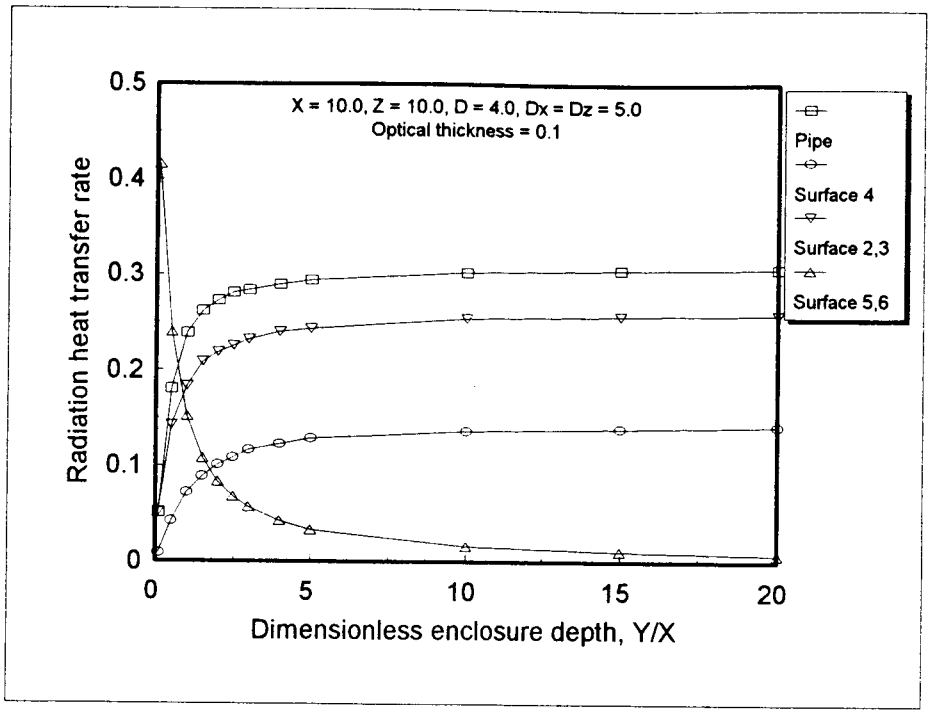
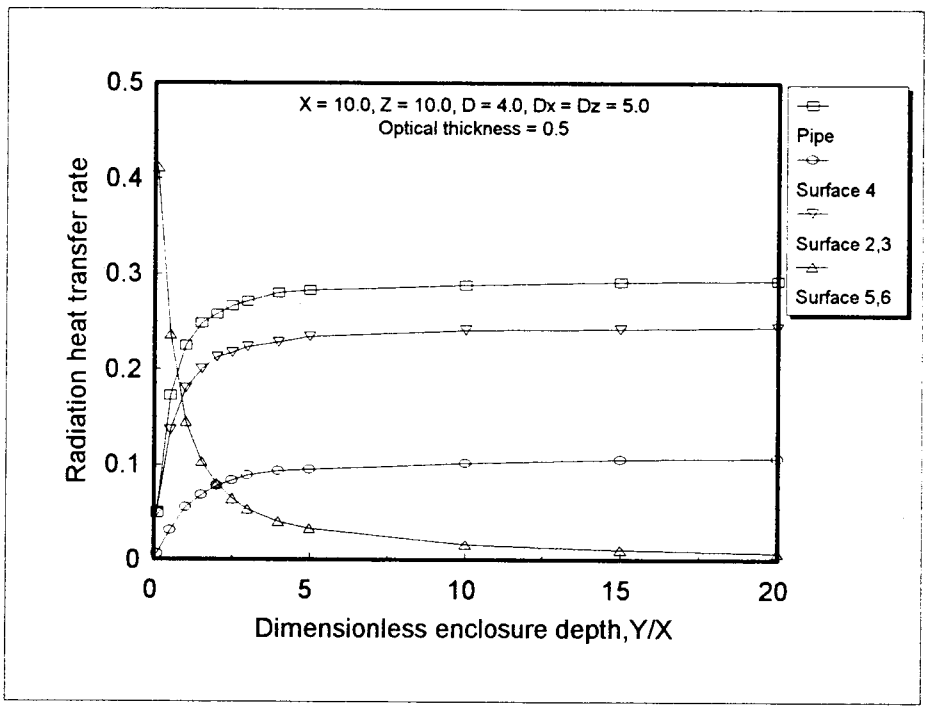


Figure 19. Variation of radiation heat transfer rate on pipe with enclosure depth and optical thickness

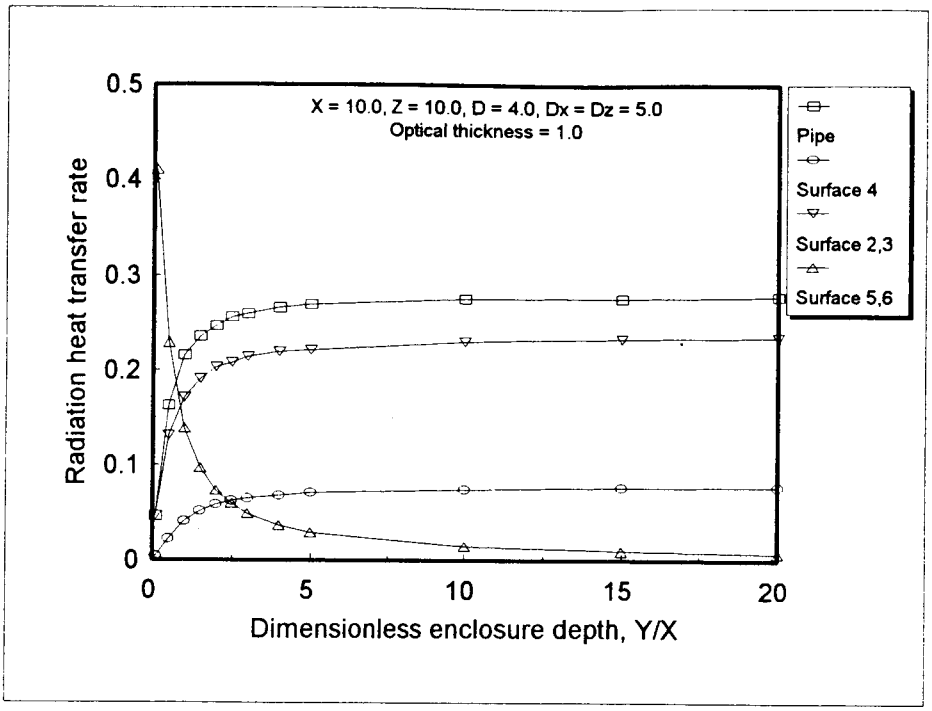


(a) $\tau = 0.1$

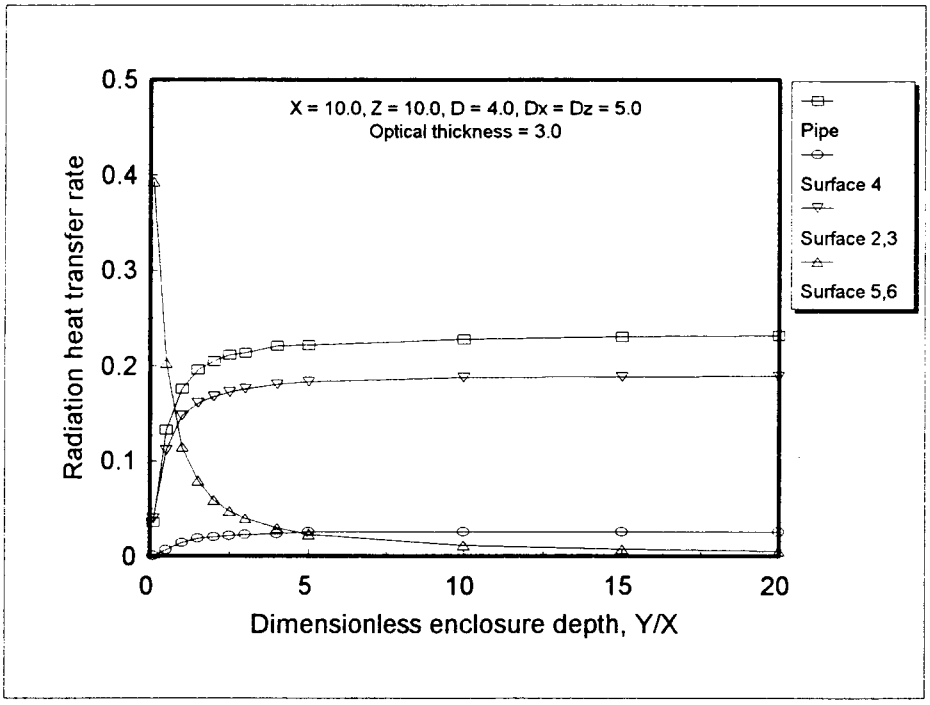


(b) $\tau = 0.5$

Figure 20. Variation of radiation heat transfer rate with enclosure depth (τ = 0.1, 0.5, 1.0, 3.0, 5.0, 10.0)

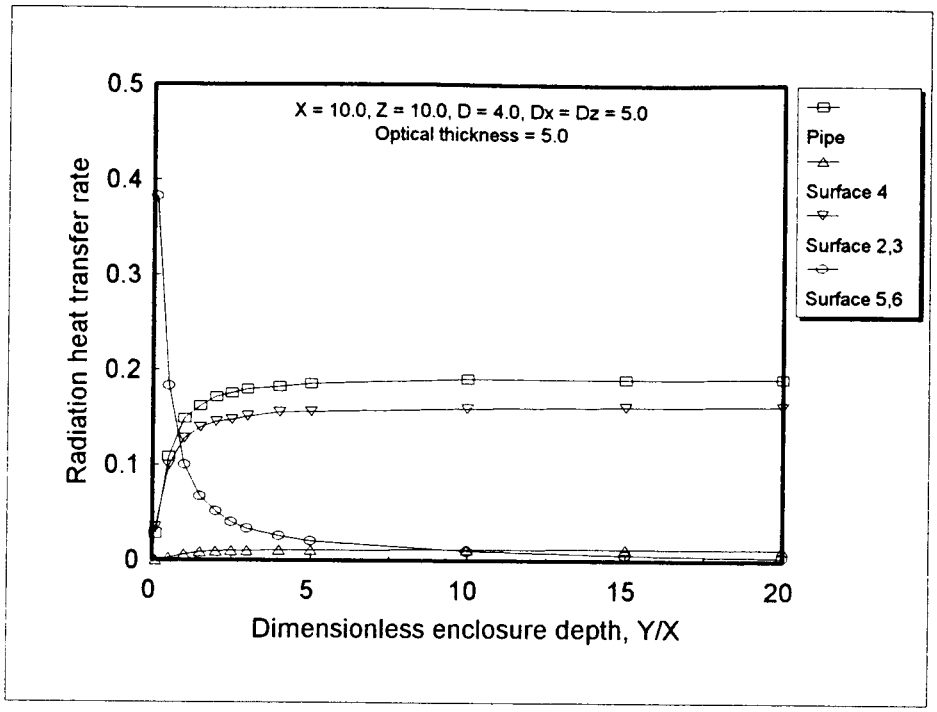


(c) $\tau = 1.0$

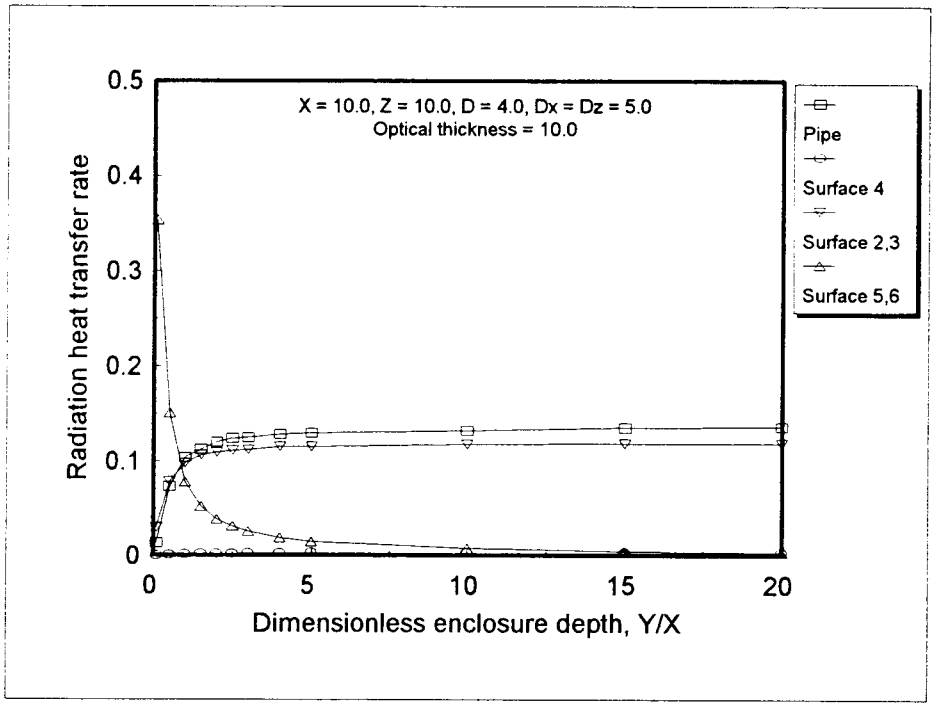


(d) $\tau = 3.0$

Figure 20. (continued)



(e) $\tau = 5.0$



(f) $\tau = 10.0$

Figure 20. (continued)

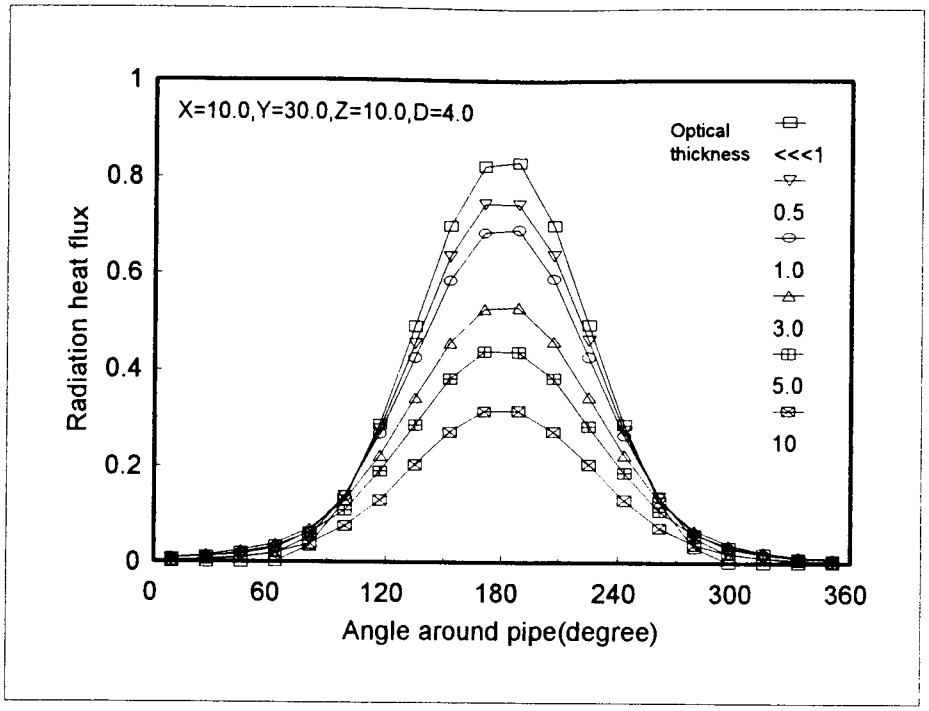


Figure 21. Distribution of radiation heat flux around pipe at y = Y/2 with optical thickness

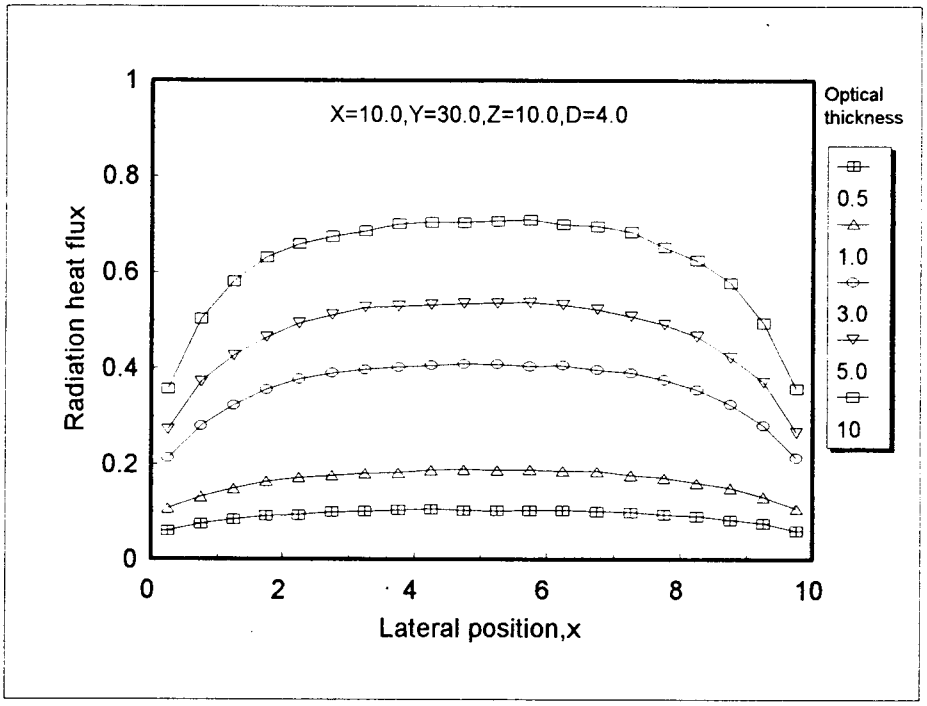


Figure 22. Distribution of radiation heat flux to center line of bottom surface at y = Y/2 with optical thickness

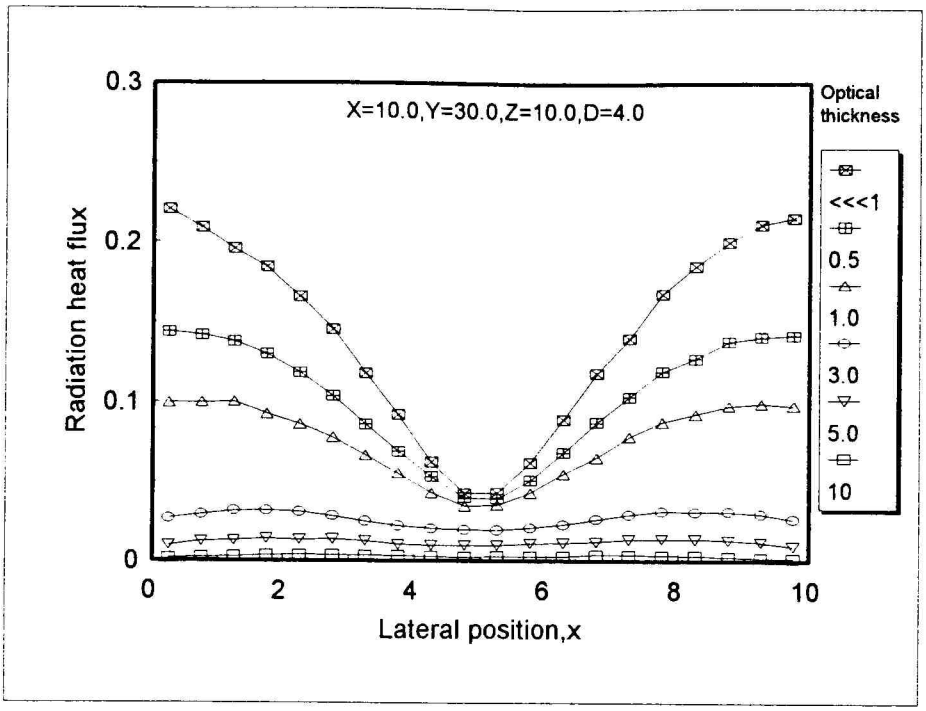


Figure 23. Distribution of radiation heat flux to center line of top surface at y = Y/2 with optical thickness

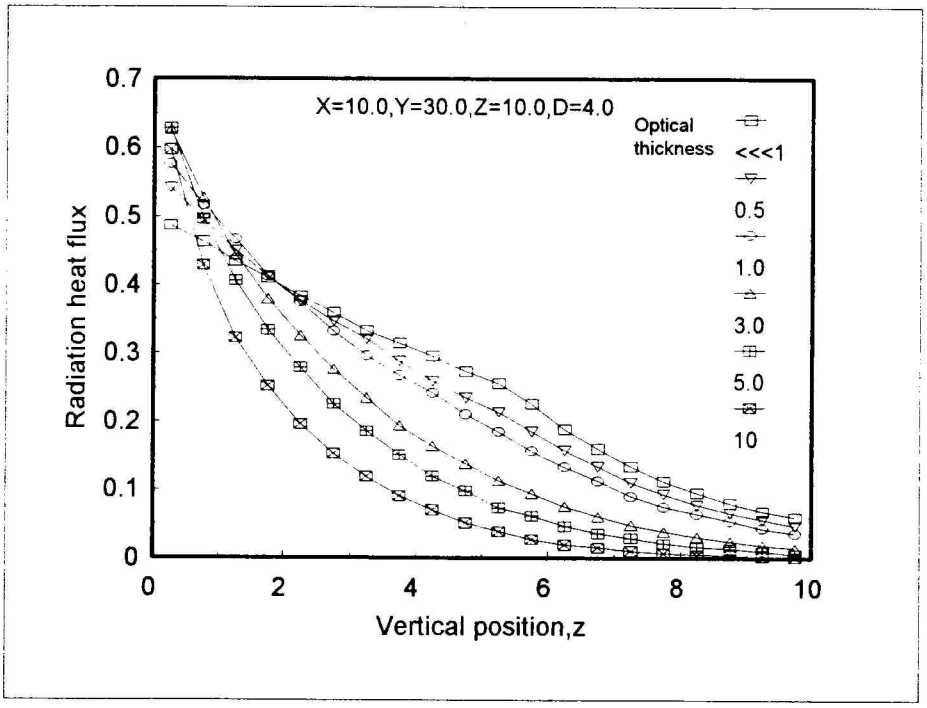
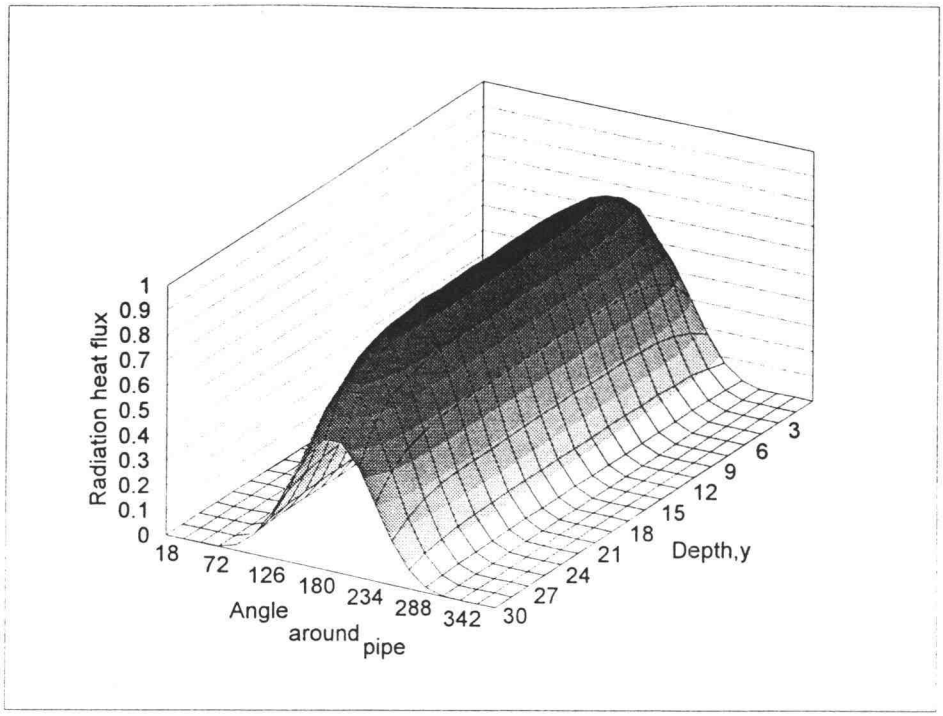
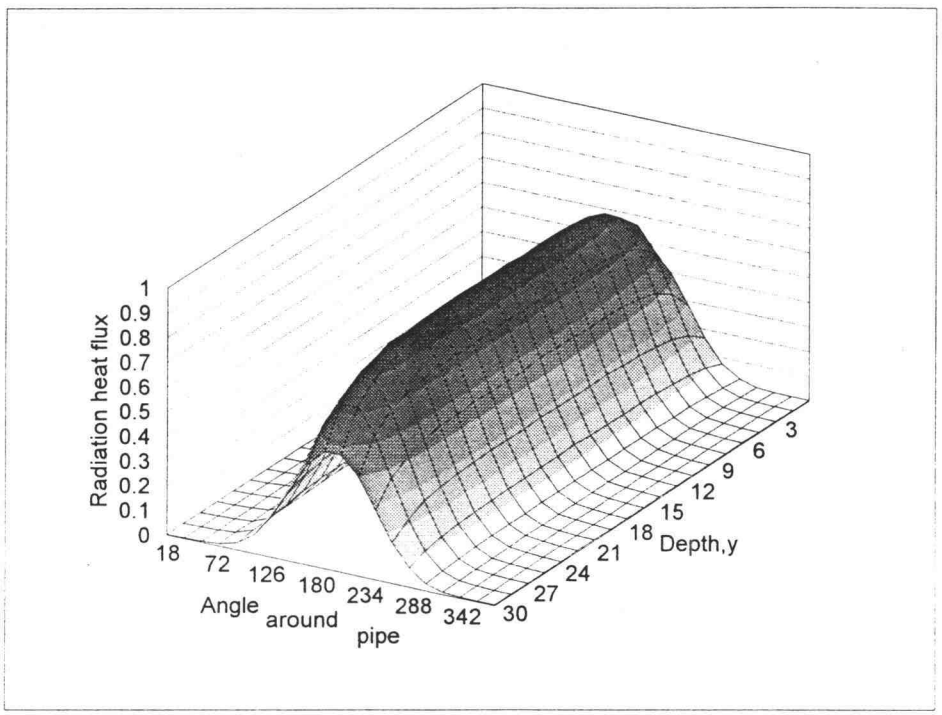


Figure 24. Distribution of radiation heat flux to center line of side wall at y = Y/2 with optical thickness

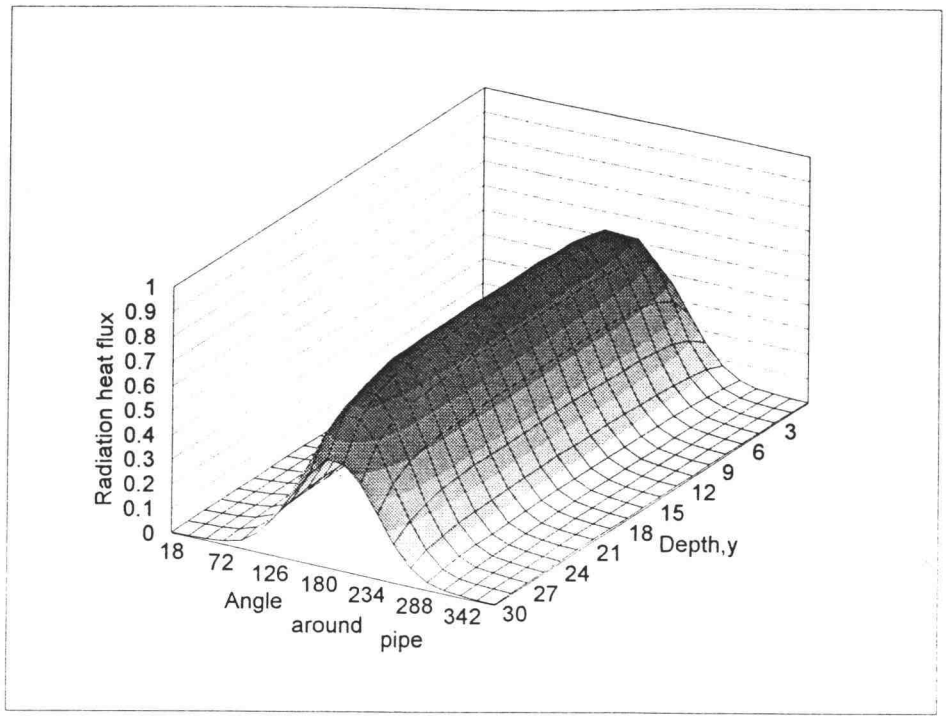


(a) $\tau << 1.0$

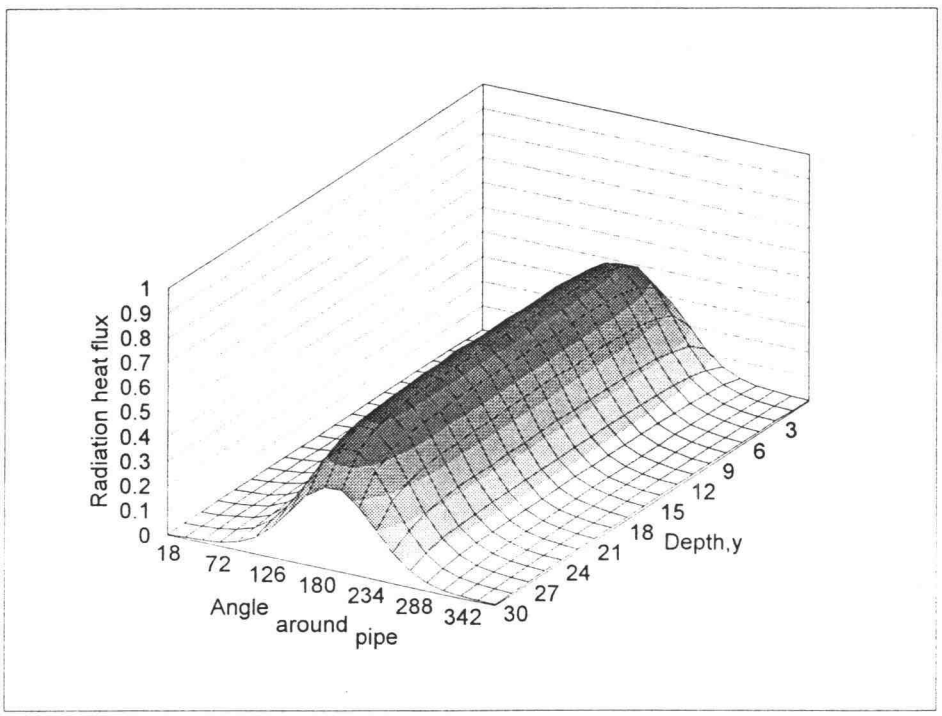


(b) $\tau = 0.5$

Figure 25. Distribution of radiation heat flux around pipe surface ($\tau = << 1.0$, 0.5, 1.0, 3.0, 5.0, 10.0)

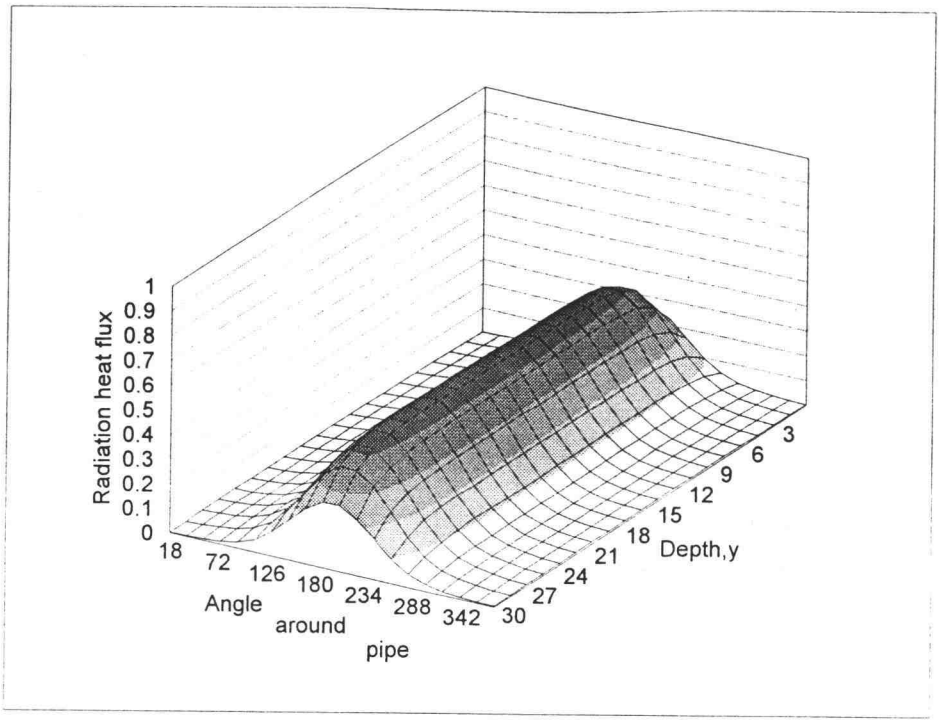


(c) $\tau = 1.0$

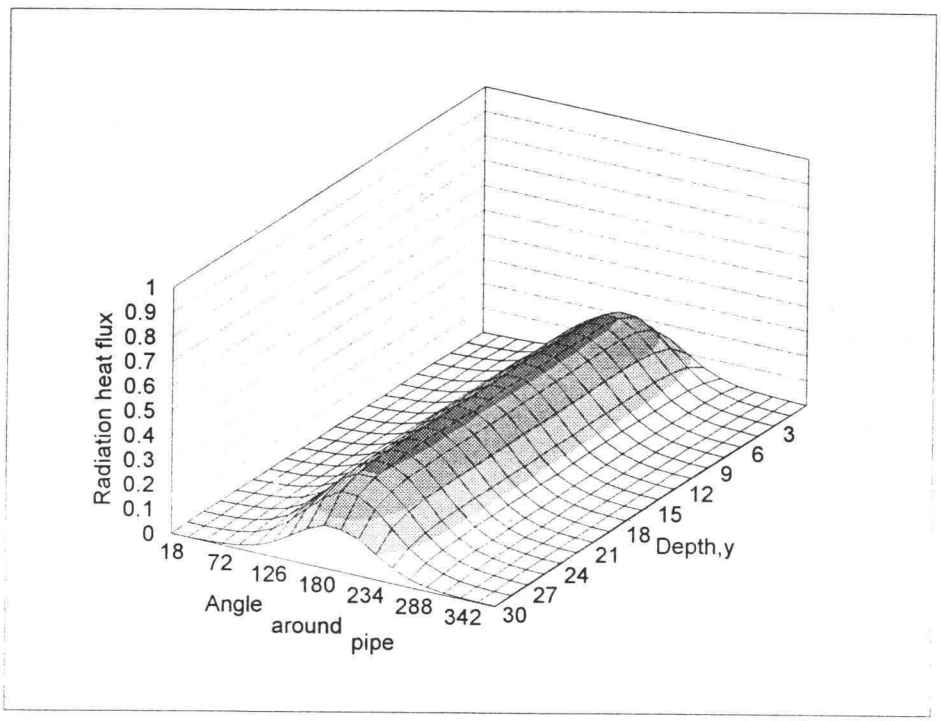


(d) $\tau = 3.0$

Figure 25. (continued)

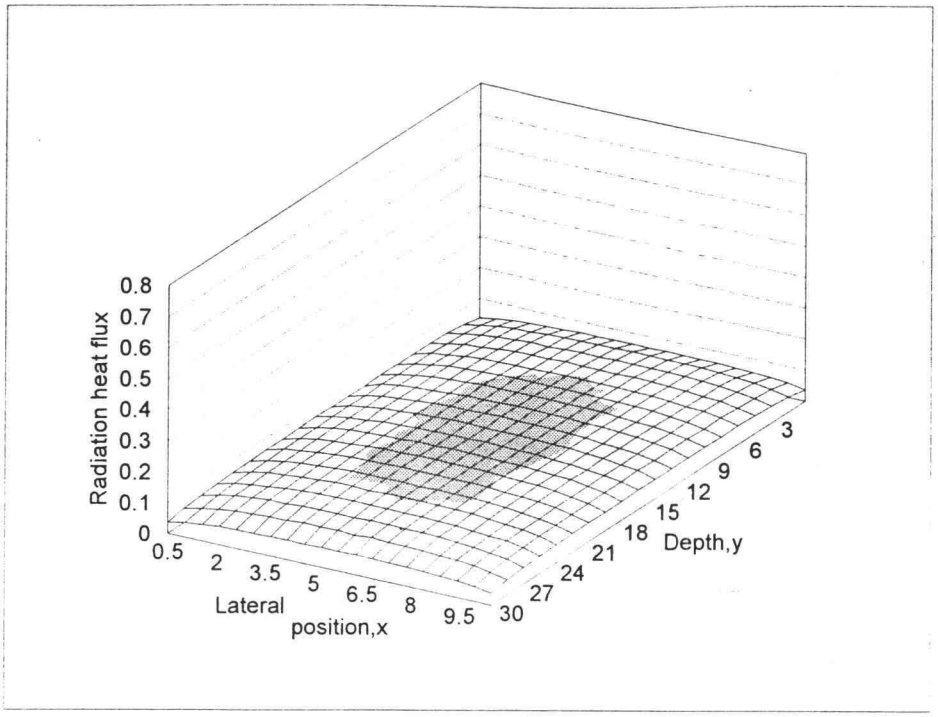


(e) $\tau = 5.0$

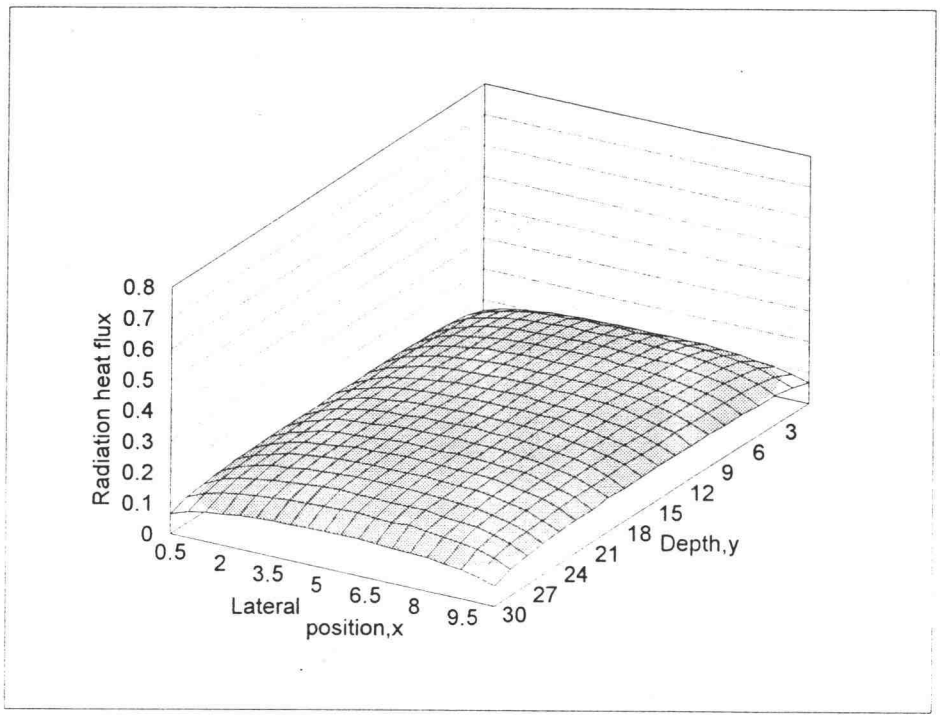


(f) $\tau = 10.0$

Figure 25. (continued)

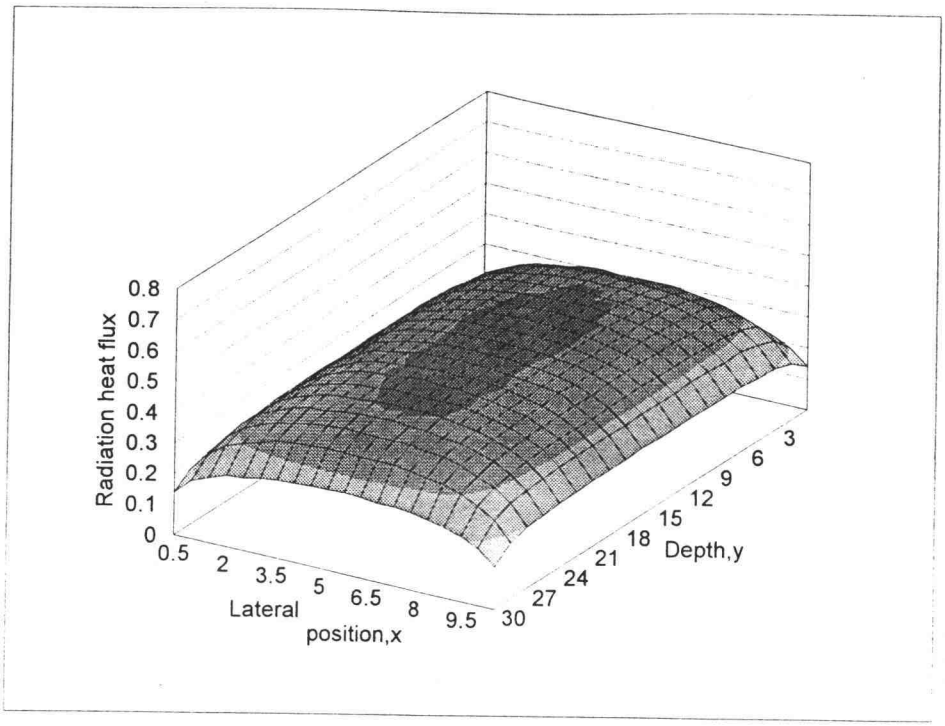


(a) $\tau = 0.5$

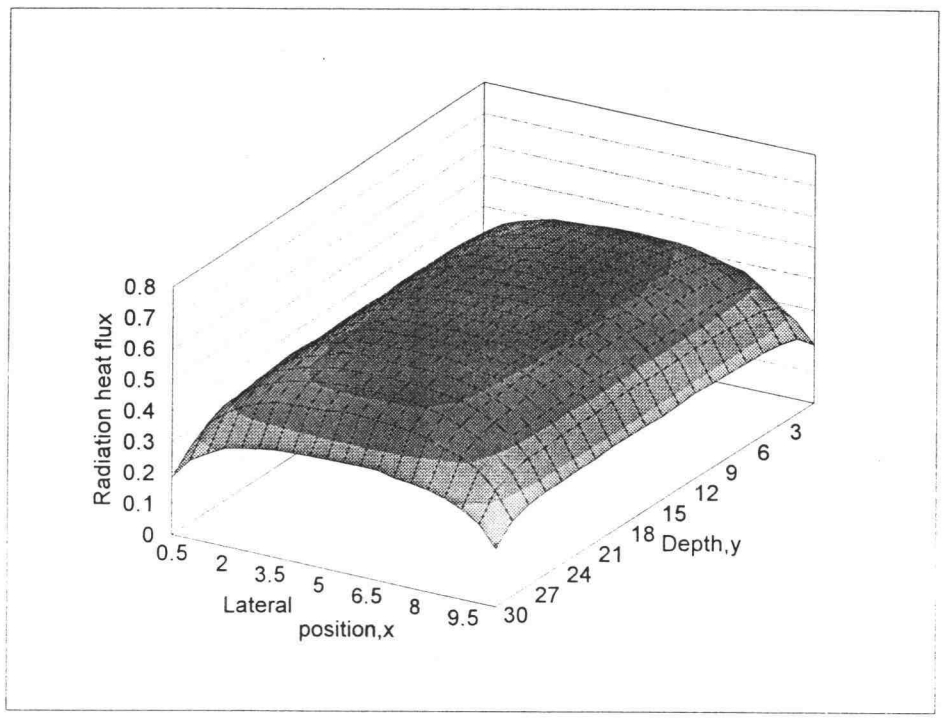


(b) $\tau = 1.0$

Figure 26. Distribution of radiation heat flux on bottom surface ($\tau = 0.5, 1.0, 3.0, 5.0, 10.0$)

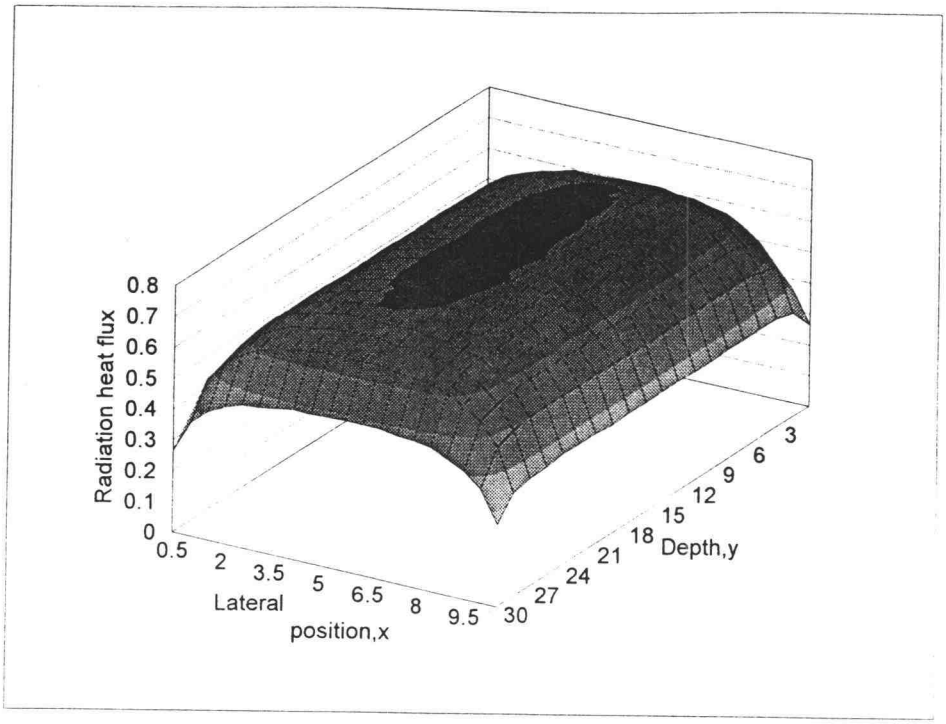


(c) $\tau = 3.0$

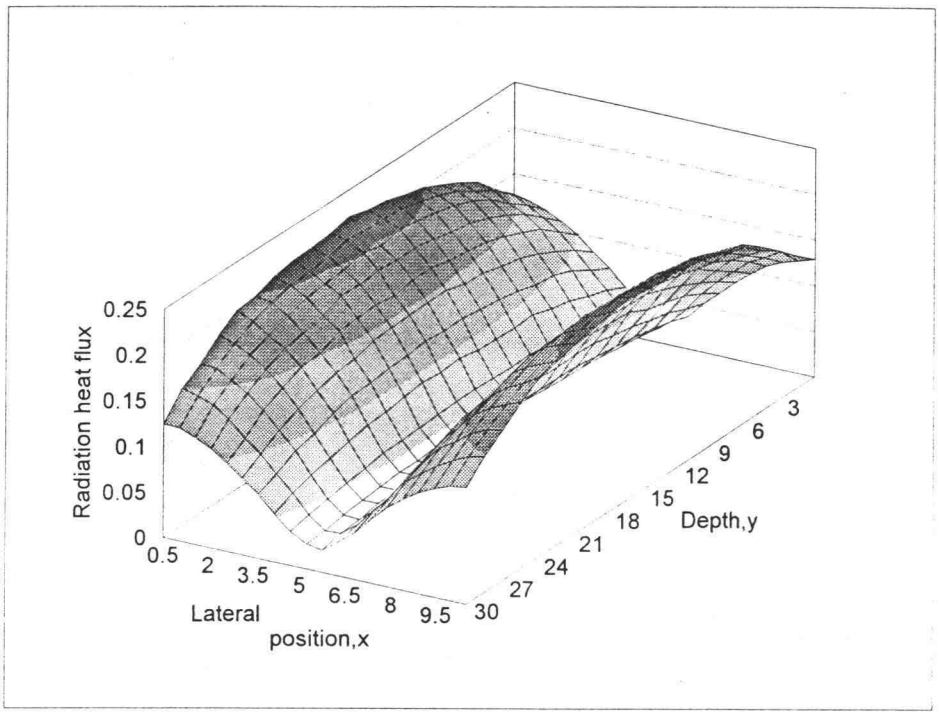


(d) $\tau = 5.0$

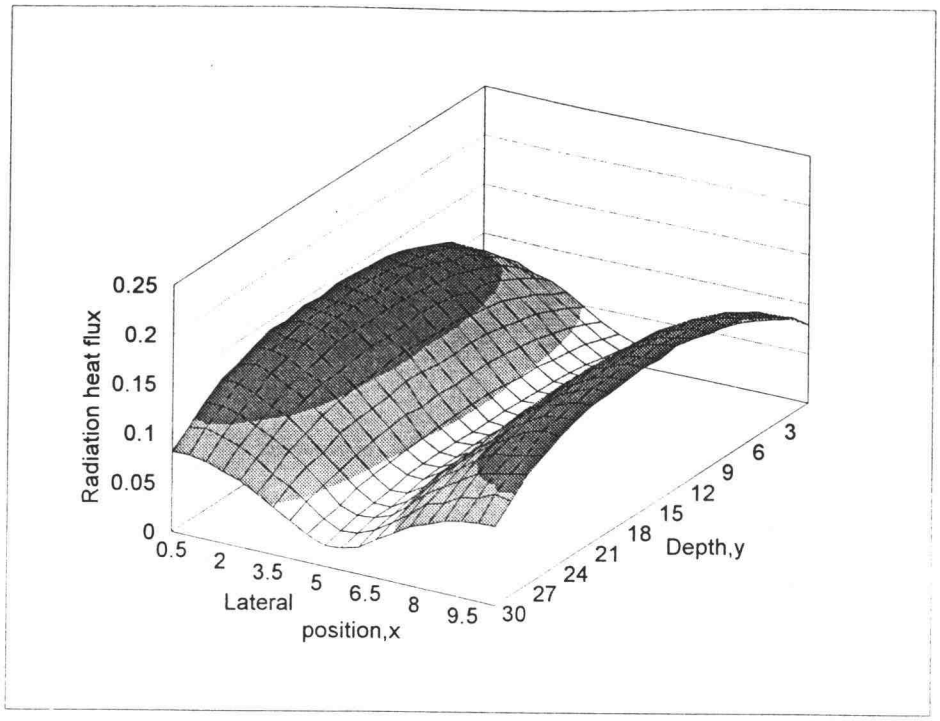
Figure 26.(continued)



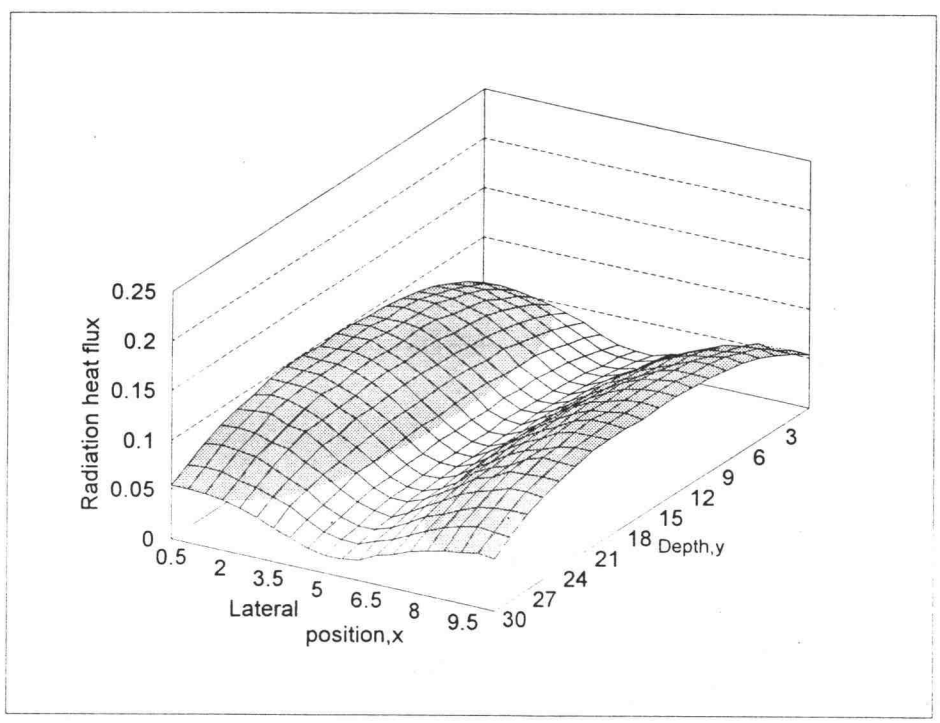
(e) $\tau = 10.0$
Figure 26. (continued)



(a) $\tau << 1.0$
Figure 27. Distribution of radiation heat flux on top surface ($\tau = << 1.0$, 0.5, 1.0, 3.0, 5.0, 10.0)

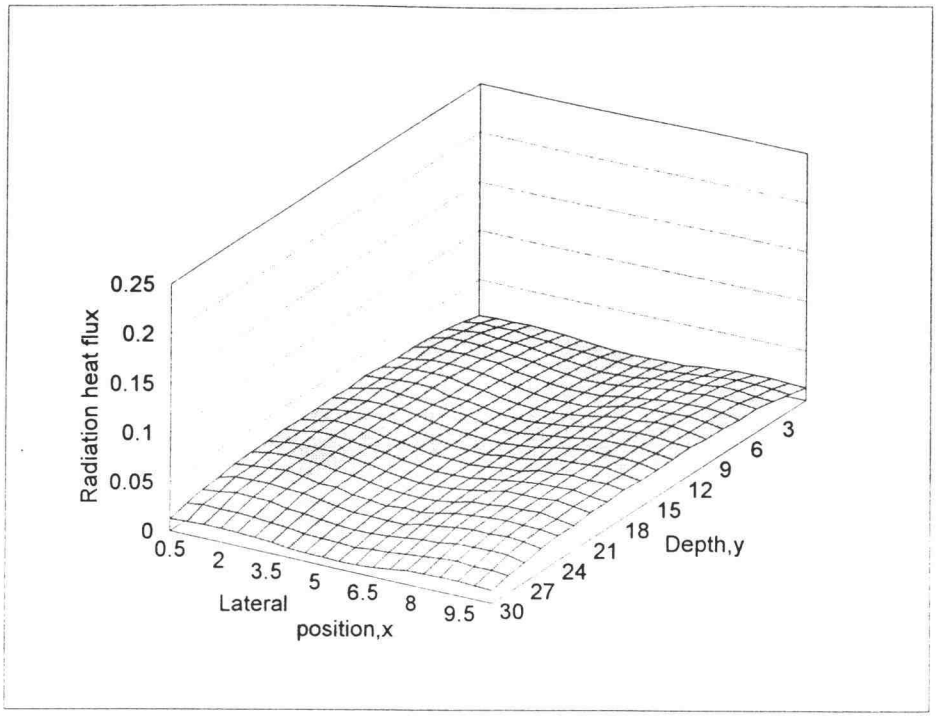


(b) $\tau = 0.5$

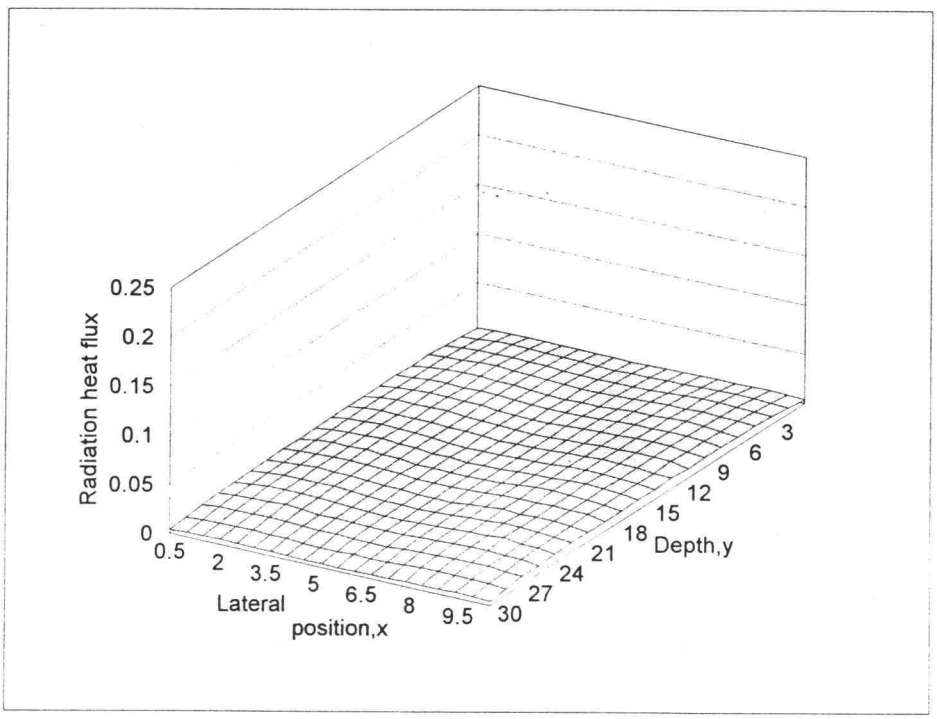


(c) $\tau = 1.0$

Figure 27. (continued)

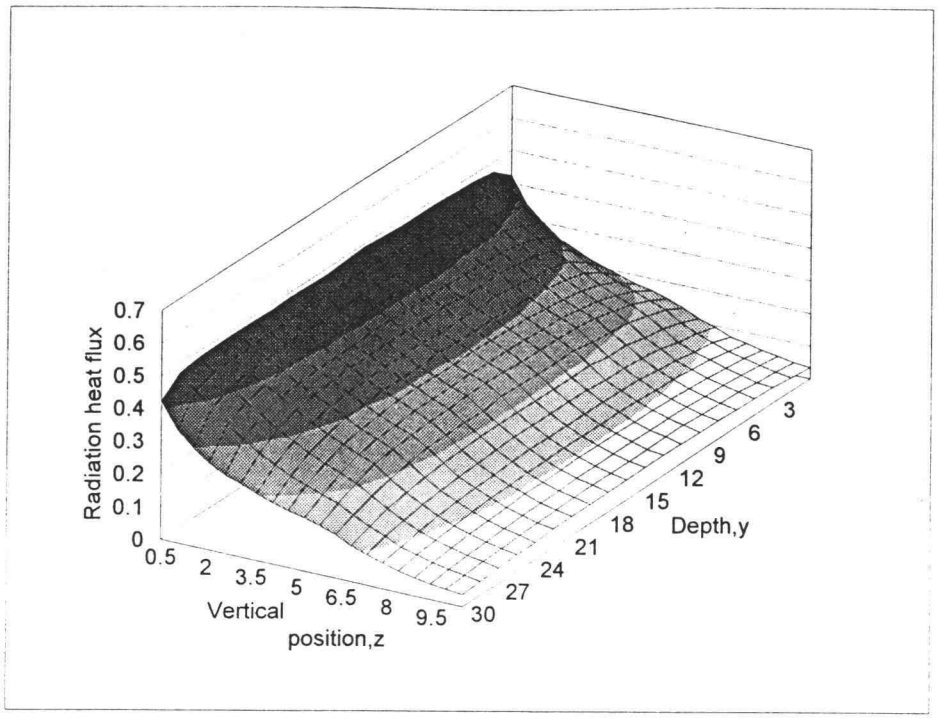


(d) $\tau = 3.0$

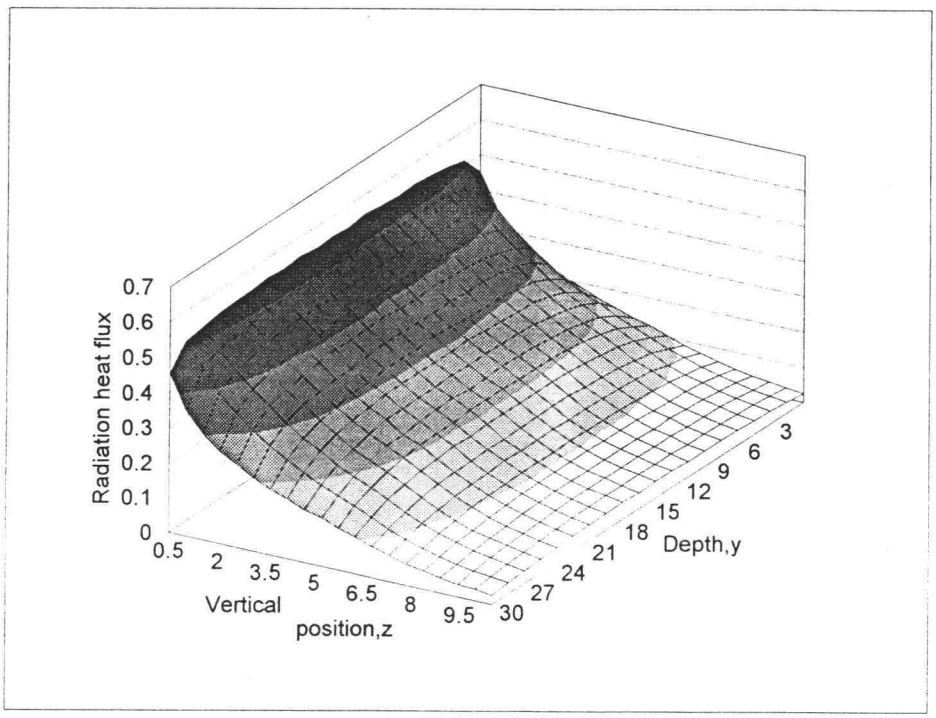


(e) $\tau = 5.0$

Figure 27. (continued)

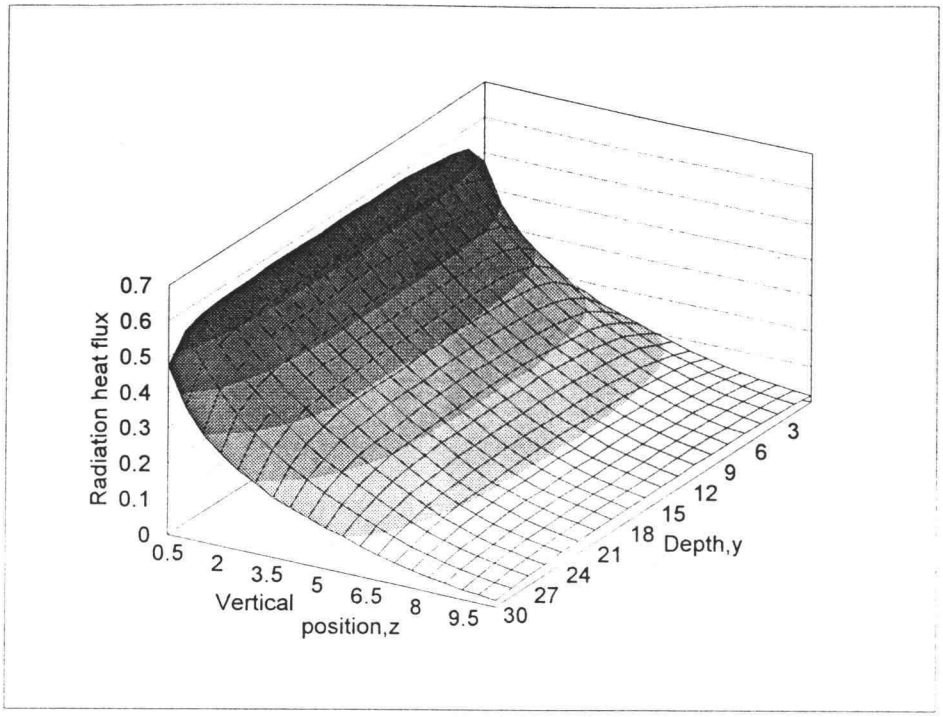


(a) $\tau << 1.0$

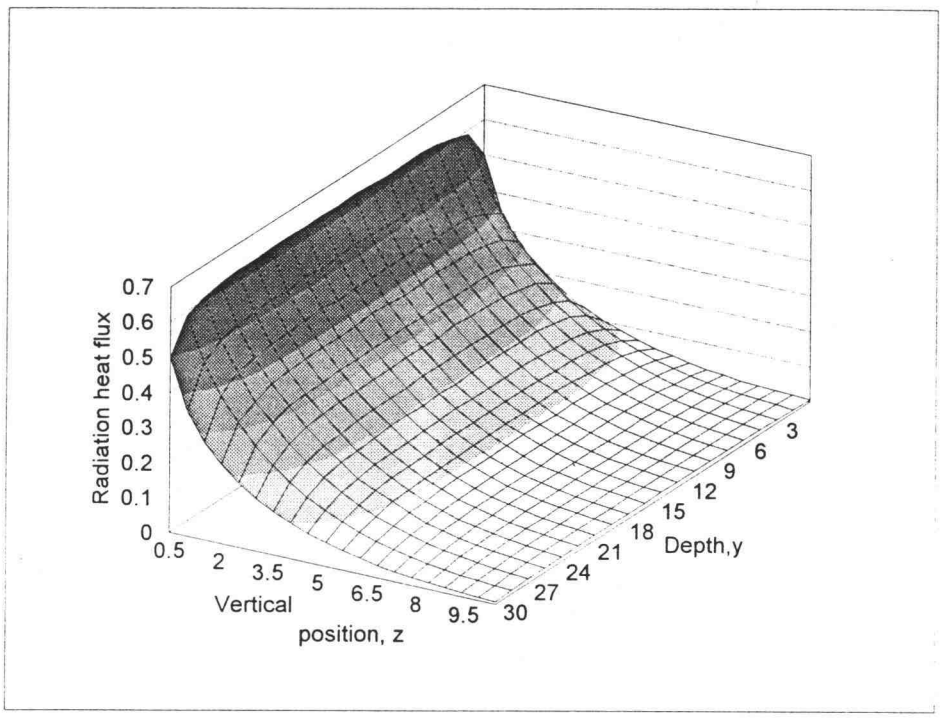


(b) $\tau = 0.5$

Figure 28. Distribution of radiation heat flux on side walls ($\tau = << 1.0$, 0.5, 1.0, 3.0, 5.0, 10.0).

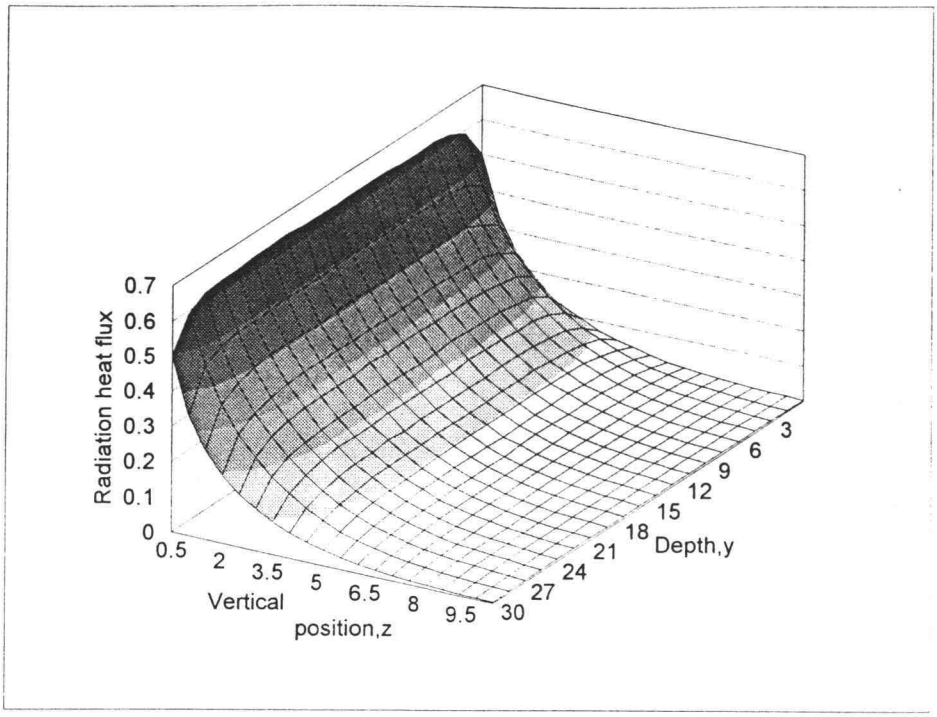


(c) $\tau = 1.0$

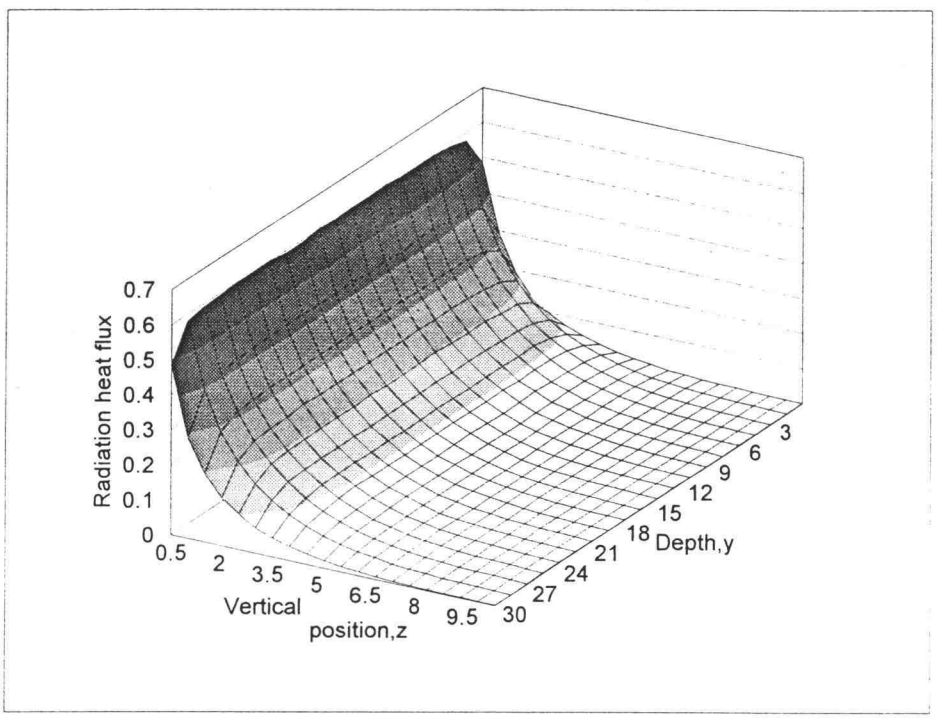


(d) $\tau = 3.0$

Figure 28. (continued)

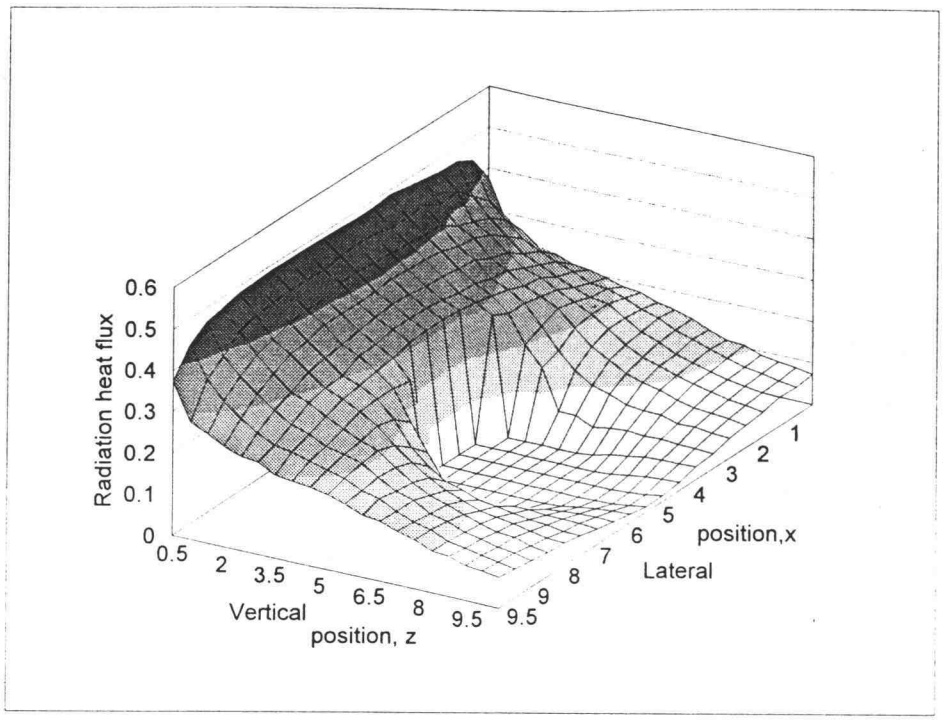


(e) $\tau = 5.0$

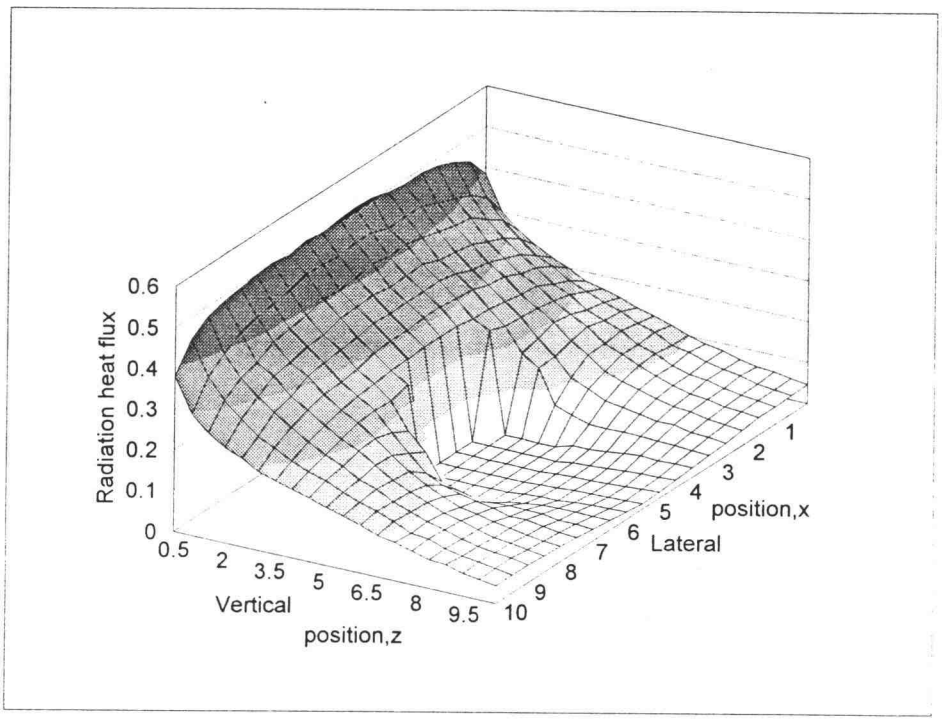


(f) $\tau = 10.0$

Figure 28. (continued)

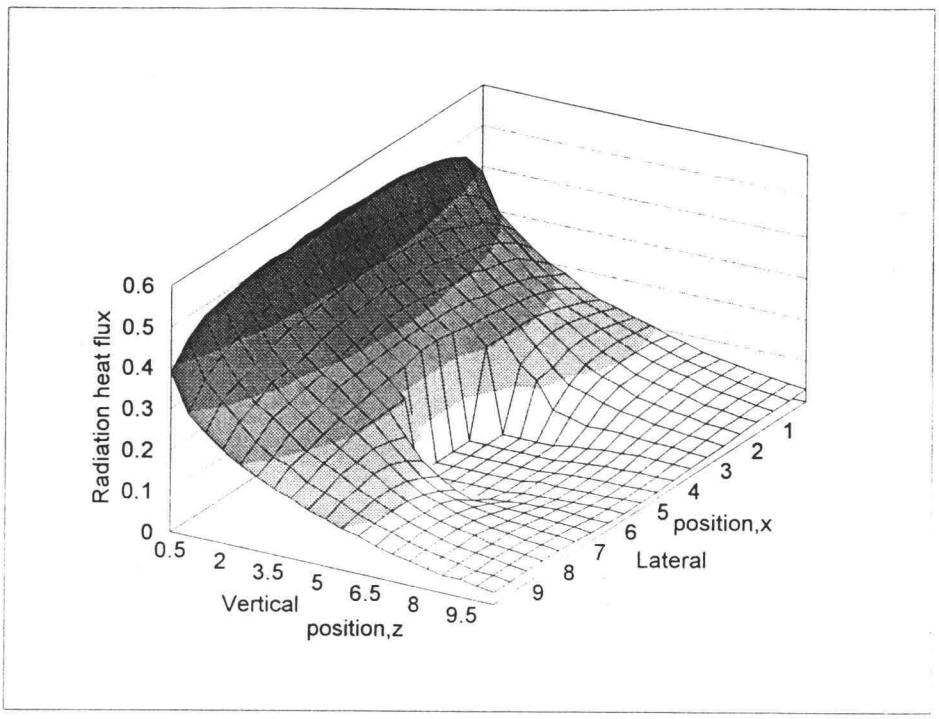


(a) $\tau << 1.0$

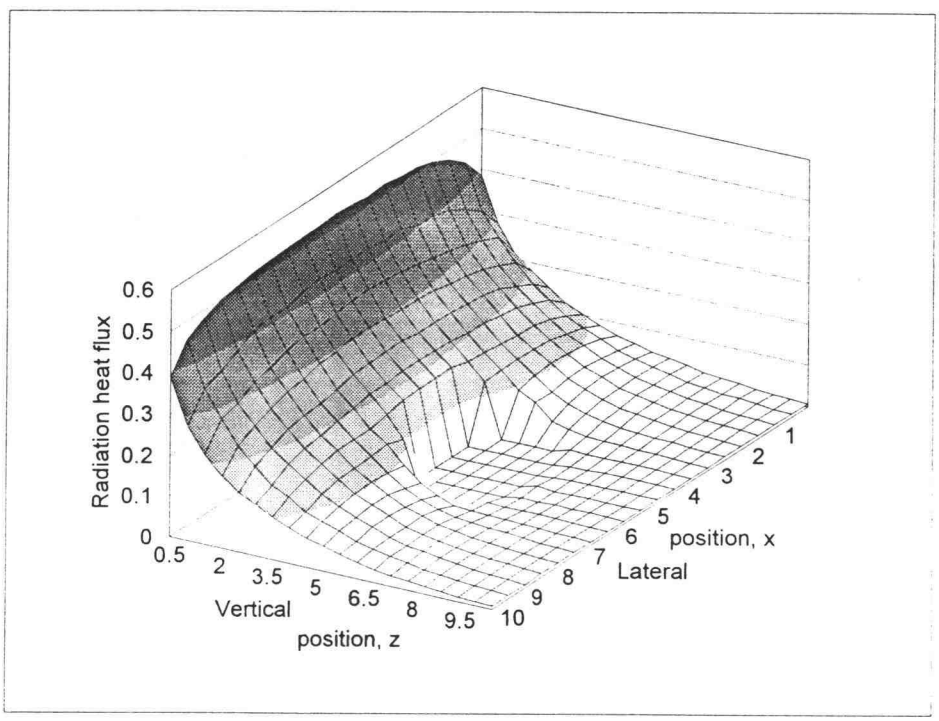


(b) $\tau = 0.5$

Figure 29. Distribution of radiation heat flux on wall 5,6 ($\tau = << 1.0$, 0.5, 1.0, 3.0, 5.0, 10.0).

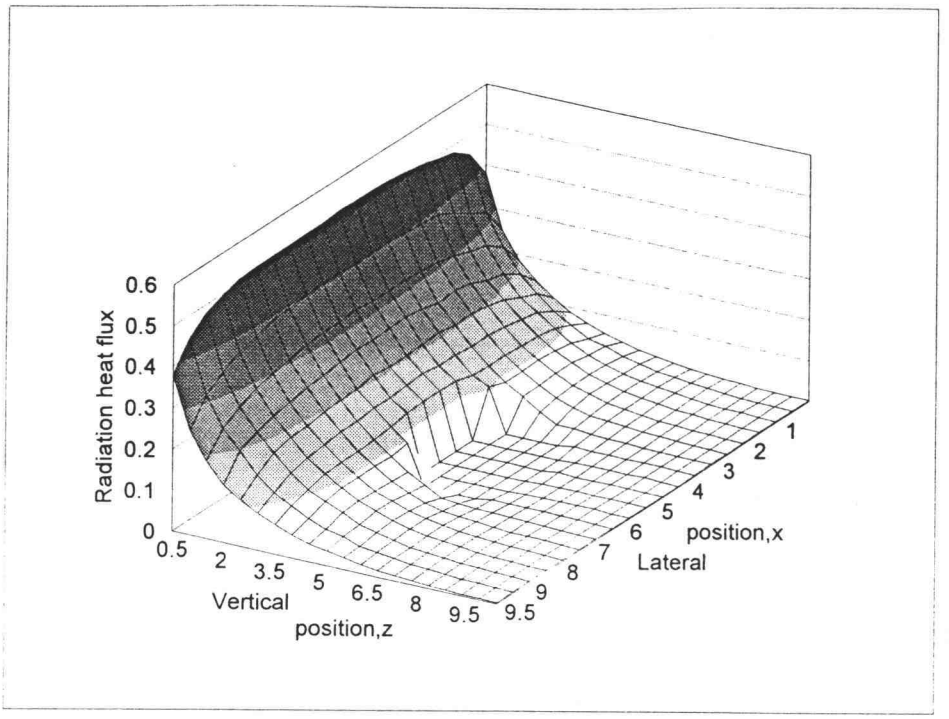


(c) $\tau = 1.0$

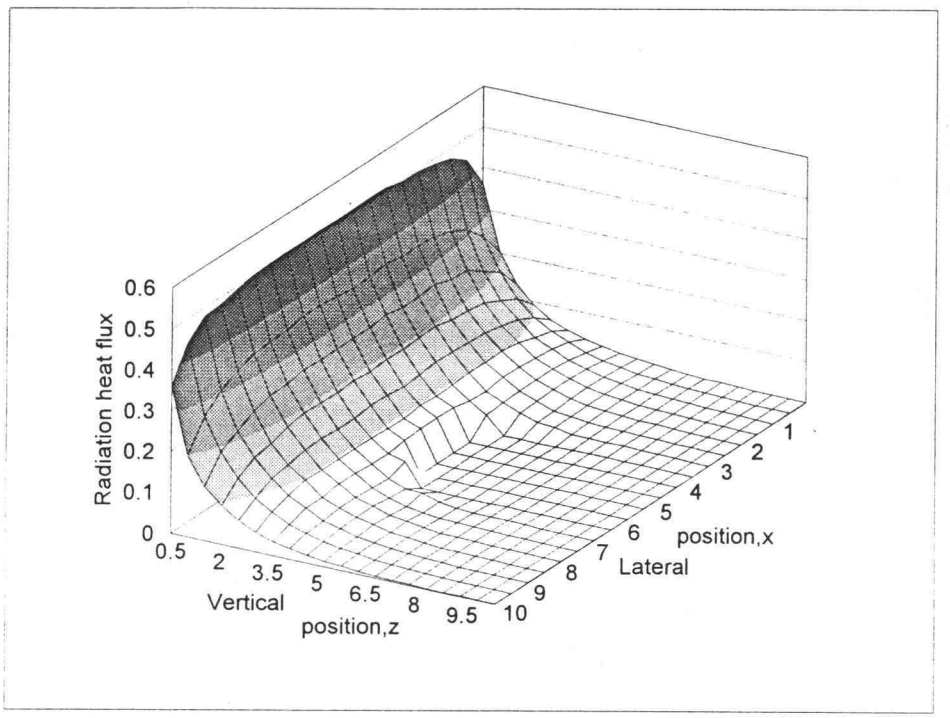


(d) $\tau = 3.0$

Figure 29. (continued)



(e) $\tau = 5.0$



(f) $\tau = 10.0$

Figure 29. (continued)

CHAPTER 6

CONCLUSIONS

A Monte Carlo method has been developed and applied to predict the distribution of radiation heat flux within an enclosure containing a horizontal pipe, which also contains a medium which has absorbing, emitting and isotropic scattering characteristics. The MCHO3D Monte Carlo code was developed for this three-dimensional geometry and was applied to one- and two-dimensional cases for validation. The three-dimensional results present useful information for design purposes in readily-usable form.

The amount of radiative energy transferred to the enclosed pipe depends on its location, the optical thickness of the participating medium, and enclosure depth. The maximum radiant transfer to a pipe located in the center of the rectangular enclosure was found to be at a dimensionless enclosure configuration, Y/X, between 3 and 5. For the optically thin case ($\tau \ll 1$) radiation heat transfer rates can be determined using geometrical view factors.

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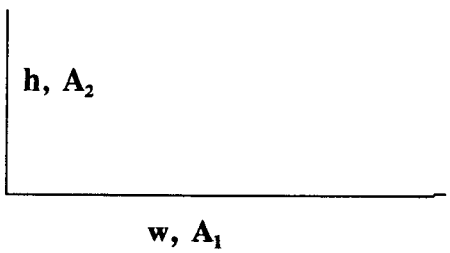
APPENDICES

APPENDIX 1

Radiative heat flux between perpendicular surfaces

The geometric view factor for two infinitely long plates of unequal widths, **h**, and, **w**, having one common edge and oriented 90° to each other, is [7]



$$F_{1\text{-}2} = \frac{1}{2}\left[1 + \frac{h}{w} - \sqrt{1 - \left(\frac{h}{w}\right)^2}\right] \qquad \text{(A-1)}$$

Where **w** is the unit length, **n** is the number of segments in unit length **w** giving **h** = **w** / **n**. In Monte Carlo method the energy per bundle is constant and the view factor is the ratio of bundles absorbed at A_2 to the total number of bundles emited from A_1. The dimensionless radiative heat flux on A_2 then becomes

$$q_{A_2} = nF_{1\text{-}2} = \frac{1}{2}\left(n + 1 - \sqrt{n^2 + 1}\right) \qquad \text{(A-2)}$$

The dimensionless radiative heat flux q_{A2} approaches 0.5 when $n \to \infty$.

APPENDIX 2

Program listing for MCHO3D

```
c-------------------------------------------------------------
c                    *** MCHO3D ***
c
c   This program calculate the radiative heat transfer in the
c   configuration system participation media shown in Fig.1.1
c              by the Monte Carlo method.
c                    Hong, Seung-Ho
c            Oregon State Univ..Mechanical Eng..
c                    (09/06/'93)
c-------------------------------------------------------------
      program mcho3d
c
      include 'com.for'
c
      open(unit = 6,file ='out3d.out',status='old')
      call input
c
c  Define initial condition of veriables.
c  absco : absorbtion coefficient of media
c
      pi = 4.0d00 * atan(1.0d00)
      absco = ot/hig

      do 30 i = 1,kx
        do 10 j = 1,ky
          ns1(i,j) = 0
          ns4(i,j) = 0
10      continue
        do 20 j = 1,kz
          ns5(i,j) = 0
          ns6(i,j) = 0
20      continue
30    continue
      do 50 i = 1,ky
        do 40 j = 1,kz
          ns2(i,j) = 0
          ns3(i,j) = 0
40      continue
50    continue
```

```
      do 80 i = 1,kx
        do 70 j = 1,ky
          do 60 k = 1,kz
            nsa(i,j,k) = 0
60          continue
70        continue
80    continue
      do 100 i = 1,kz
        do 90 j = 1,kp
          nsp(i,j) = 0
90        continue
100   continue
c-----------------------------------------------------------------
c              ********** MCHO3D start **********
c-----------------------------------------------------------------

      x = ran3(-74432333)
c
      do 999 ii = 0, nuemy - 1
c
        print*,ii

        buny = (2*ii+1)*alen/2.0/nuemy
c
        do 888 jj = 0, nuemx - 1
c
          bunx = (2*jj+1) * width / 2.0 / nuemx
          do 777 kk = 1,npn
c
          x = bunx
          y = buny
          z = 0.0d00
          eta = 0.0d00
c
c  Initial direction of bundle from the source
c
          theta = asin(sqrt(ran3(0)))
          phi = 2.0d00 * pi * ran3(0)
          rx = sin(theta)*cos(phi)
          ry = sin(theta)*sin(phi)
          rz = cos(theta)
          call caleta(eta,rx,rz)
c
c     Path length of emitting bundle through the media
c
```

```
 1000     s = -1.0d00 / absco * dlog(ran3(0))
c
c   start from pipe.If the direction of bundle is not pipe
c   the direction will be walls
c
c   ixx = 1 means that bundle is absobed by wall
c   ixx = 2 means that bundle is reflected
c   ixx = 3 means that bundle dosen't reach to the wall
c
 666      rxnew = sin(eta)
         rynew = sin(phi)
         rznew = cos(eta)
         sdc = sqrt((dx-x)**2+(dz-z)**2)
         sig2 = asin(dia/2.0d00/sdc)
c
         if(x.ge.dx.and.z.ge.dz) then
           if((dx-x).eq.0.0d00) then
             sigma = pi
             sig3 = pi + sig2
             sig4 = pi - sig2
           else
             if((dz-z).eq.0.0d00) then
               sigma = 1.5d00 * pi
             else
               sigma = 1.5d00 * pi - atan((dz-z)/(dx-x))
             endif
             sig3 = sigma + sig2
             sig4 = sigma - sig2
           endif
c
           rdz3 = cos(sig3)
           rdx4 = sin(sig4)
c
           if(rznew.lt.rdz3.and.rxnew.lt.rdx4) then
             call pipe
             goto(777,666,1000)ixx
           else
             call wall
             goto(777,666,1000)ixx
           endif
c
         elseif(x.lt.dx.and.z.gt.dz) then
           sigma = pi/2.0d00 + atan(abs((dz-z)/(dx-x)))
           sig3 = sigma - sig2
           sig4 = sigma + sig2
```

```
          rdz3 = cos(sig3)
          rdx4 = sin(sig4)
c
          if(rznew.lt.rdz3.and.rxnew.gt.rdx4) then
            call pipe
            goto(777,666,1000)ixx
          else
            call wall
            goto(777,666,1000)ixx
          endif
c
        elseif(x.le.dx.and.z.le.dz) then
c
          if((dx-x).eq.0.0d00) then
            sigma = 0.0d00
            sig3 = sig2
            sig4 = 2.0d00 * pi - sig2
          else
            if((dz-z).eq.0.0d00) then
              sigma = pi/2.0d00
            else
              sigma = atan((dx-x)/(dz-z))
            endif
            sig3 = sigma + sig2
            sig4 = 2.0d00 * pi + sigma - sig2
          endif
c
          rdz3 = cos(sig3)
          rdx4 = sin(sig4)
c
          if(rznew.gt.rdz3.and.rxnew.gt.rdx4) then
            call pipe
            goto(777,666,1000)ixx
          else
            call wall
            goto(777,666,1000)ixx
          endif
c
        elseif(x.gt.dx.and.z.lt.dz) then
          sigma = 1.5d00 * pi + atan(abs((dz-z)/(dx-x)))
          sig3 = sigma - sig2
          sig4 = sigma + sig2
          rdz3 = cos(sig3)
          rdx4 = sin(sig4)
c
```

```
            if(rznew.gt.rdz3.and.rxnew.lt.rdx4) then
              call pipe
              goto(777,666,1000)ixx
            else
              call wall
              goto(777,666,1000)ixx
            endif
c
          else
            print*,'something wrong in celecting hitting direction'
            goto 555
          endif
c
  777   continue
  888   continue
  999 continue
c
      call output

  555 stop
      end

c-----------------------------------------------------------------
c   This subroutine calculate the bundle history. The bundle is
c   moving toward pipe.  So after the bundle impacts with pipe
c   two cases will be occur in pipe, absorption or reflection.
c-----------------------------------------------------------------

      subroutine pipe
c
      include 'com.for'
c
      xold = x
      yold = y
      zold = z
      sold = s
      sxz = s * sqrt(rx**2 + rz**2)
      sdcold = sqrt((dx-xold)**2+(dz-zold)**2)
      sig2 = asin(dia/2.0d00/sdcold)
      sxznew = sdcold * cos(sig2)
c
      if(sxz.gt.sxznew) then
        sxz = sxznew
      endif
c
```

```
      x = xold + sxz * rxnew
      z = zold + sxz * rznew
      sdc = sqrt((dx-x)**2+(dz-z)**2)
c
c   Does the bundle impects with the pipe ?
c
      if(sdc.lt.dia/2.0d00) then
        ddx = dx - xold
        ddz = dz - zold
        sdotr = rxnew * ddx + rznew * ddz
        rsqr = ddx**2 + ddz**2
        sarg = sdotr**2 - (rsqr - dia**2/4.0d00)
        sxz = sdotr - sqrt(sarg)
c
c   Calculate impect point of bundle with pipe
c
        s = sxz / sqrt(rx**2 + rz**2)
        x = xold + s * rx
        y = yold + s * ry
        z = zold + s * rz
c
c  Does the bundle hit the surface 5 or 6 before hit the pipe ?
c
        if(y.le.0.0d00) then
          call surface5
        elseif(y.gt.alen) then
          call surface6
        else
c
c   The bundle hits the pipe
c
          rx = (x-dx)/(dia/2.0d00)
          rz = (z-dz)/(dia/2.0d00)
c
c   Change the impect point to angle value(from 0 to 2pi)
c
          if(rx.ge.0.0d00.and.rz.gt.0.0d00) then
            eta = atan(rx/rz)
          elseif(rx.ge.0.0d00.and.rz.eq.0.0d00) then
            eta = pi/2.0d00
          elseif(rz.le.0.0d00) then
            if(rx.lt.0.0d00.and.rz.eq.0.0d00) then
              eta = 1.5d00*pi
            else
              eta = pi + atan(rx/rz)
```

```
            endif
          else
            eta = 2.0d00*pi + atan(rx/rz)
          endif
c
c   Does the bundle absorb by the pipe ?
c
          if(ran3(0).le.abop) then
            ixx = 1
            do 100 i = 1,ky
              if(y.le.alen*i/ky) then
                ni = i
                goto 200
              endif
100           continue
200           do 300 j = 1,kp
                ramda2 = 2.0d00 * pi * j / kp
                if(eta.le.ramda2) then
                  nsp(ni,j) = nsp(ni,j) + 1
                  goto 400
                endif
300           continue
c
c   Because the bundle does not absorbed, it will be reflected. So
c   generate new random numbers and calculate "thetap" and "phip"
c       for new direction of the bundle emitted from pipe.
c
          else
            ixx = 2
            s = sold - s
            theta = asin(sqrt(ran3(0)))
            phi = 2.0d00 * pi * ran3(0)
            rx = sin(theta) * cos(phi)
            ry = sin(theta) * sin(phi)
            rz = cos(theta)
c
c   Calculate new direction based on x-z coordinate
c
            sr = sqrt(rx**2 + rz**2)
            pi = 4.0d00 * atan(1.0d00)
c
            if(rx.ge.0.0d00.and.rz.gt.0.0d00) then
              etap = atan(rx/rz)
            elseif(rx.ge.0.0d00.and.rz.eq.0.0d00) then
              etap = pi / 2.0d00
```

```
            elseif(rz.le.0.0d00) then
              if(rx.lt.0.0d00.and.rz.eq.0.0d00) then
                etap = 1.5d00 * pi
              else
                etap = pi + atan(rx/rz)
              endif
            else
              etap = 2.0d00 * pi + atan(rx/rz)
            endif

            eta = eta + etap
            rx = sin(eta)
            rz = cos(eta)

            if(rx.ge.0.0d00.and.rz.gt.0.0d00) then
              etap = atan(rx/rz)
            elseif(rx.ge.0.0d00.and.rz.eq.0.0d00) then
              etap = pi / 2.0d00
            elseif(rz.le.0.0d00) then
              if(rx.lt.0.0d00.and.rz.eq.0.0d00) then
                etap = 1.5d00 * pi
              else
                etap = pi + atan(rx/rz)
              endif
            else
              etap = 2.0d00 * pi + atan(rx/rz)
            endif
c
            eta = etap
            rx = rx * sr
            rz = rz * sr
c
            s = -1.0d00 / absco * dlog(ran3(0))
            call wall
          endif
        endif
c
c   The bundle dosen't reach to the pipe. It is absorbed in the
c   gas and reemitted.
c
       else
         ixx = 3
         call gas
       endif
```

```
  400 return
      end

c-----------------------------------------------------------------
c  This subroutine calculates the bundle historz which hit
c                        the walls.
c-----------------------------------------------------------------

      subroutine wall
c
      include 'com.for'
c
      xold = x
      yold = y
      zold = z
      x = xold + s * rx
      y = yold + s * ry
      z = zold + s * rz
      rxnew = sin(eta)
      rynew = sin(phi)
      rznew = cos(eta)
c
c     Calculate walls position based on old position(xold,zold)
c     of bundle.
c
      if((xold**2 + (hig - zold)**2).eq.0.0d00) then
        r3u = 0.0d00
      else
        r3u = (hig - zold) / sqrt(xold**2 + (hig - zold)**2)
      endif
c
      if((xold**2 + zold**2).eq.0.0d00) then
        r3d = 0.0d00
      else
        r3d = -zold / sqrt(xold**2 + zold**2)
      endif
c
      if(sqrt((width-xold)**2 + (hig-zold)**2).eq.0.0d00) then
        r2u = 0.0d00
      else
        r2u = (hig-zold) / sqrt((width-xold)**2 + (hig-zold)**2)
      endif
c
      if(sqrt((width-xold)**2 + zold**2).eq.0.0d00) then
        r2d = 0.0d00
```

```
      else
        r2d = -zold / sqrt((width-xold)**2 + zold**2)
      endif
c
c     Deside direction of bundle
c
      if(rxnew.ge.0.0d00) then
        if(rznew.lt.r2d) then
          call surface1
        elseif(rznew.ge.r2d.and.rznew.lt.r2u) then
          call surface2
        else
          call surface4
        endif
      else
        if(rznew.le.r3d) then
          call surface1
        elseif(rznew.gt.r3d.and.rznew.le.r3u) then
          call surface3
        else
          call surface4
        endif
      endif
c
      return
      end

c-----------------------------------------------------------------
c     This subroutine calculates the bundle history which hit
c                        the surface 1.
c-----------------------------------------------------------------

      subroutine surface1
c
      include 'com.for'
c
      if(z.lt.0.0d00) then
        zold2 = z
        tau = zold/abs(rz)
        x = xold + tau * rx
        y = yold + tau * ry
        z = 0.0d00

        if(y.lt.0.0d00) then
          call surface5
```

```
      elseif(y.gt.alen) then
        call surface6
      else

        if(ran3(0).le.abopw) then
          ixx = 1
          do 10 i=1,kx
            if(x.le.width*i/kx) then
              ni = i
              goto 20
            endif
10        continue
20        do 30 j = 1,ky
            if(y.le.alen*j/ky) then
              ns1(ni,j) = ns1(ni,j) + 1
              goto 40
            endif
30        continue
c
c     The bundle is reflected
c
        else
          ixx = 2
          s = s-abs(zold*s/(zold2-zold))
c
c     Diffuse reflection
c
          if(ran3(0).gt.specu) then
            eta = 0.0d00
            theta = asin(sqrt(ran3(0)))
            phi = 2.0d00 * pi * ran3(0)
            rx = sin(theta) * cos(phi)
            ry = sin(theta) * sin(phi)
            rz = cos(theta)
            call caleta(eta,rx,rz)
c
c     Specular reflection
c
          else
            rx = rx
            ry = ry
            rz = -rz
            if(rx.ge.0.0d00) then
              eta = pi - eta
            else
```

```
                eta = 3.0d00 * pi - eta
              endif
            endif
          endif
        endif
c
c   Does the bundle hit the surface 5 or 6 ?
c
      elseif(y.lt.0.0d00) then
        call surface5
      elseif(y.gt.alen) then
        call surface6
c
c    The bundle is located in gas
c
      else
        ixx = 3
        call gas
      endif
c
   40 return
      end

c-----------------------------------------------------------------
c   This subroutine calculates the bundle historz which hit
c                       the surface 2.
c-----------------------------------------------------------------

      subroutine surface2
c
      include 'com.for'
c
      if(x.gt.width) then
        xold2 = x
        tau = (width-xold) / abs(rx)
        x = width
        y = yold + tau * ry
        z = zold + tau * rz

        if(y.lt.0.0d00) then
          call surface5
        elseif(y.gt.alen) then
          call surface6
        else
c
```

```
            if(ran3(0).le.abopw) then
              ixx = 1
              do 10 i=1,kz
               if(z.le.hig*i/kz) then
                 ni = i
                 goto 20
               endif
   10         continue
   20         do 30 j = 1,ky
               if(y.le.alen*j/ky) then
                 ns2(j,ni) = ns2(j,ni) + 1
                 goto 40
               endif
   30         continue
c
c     The bundle is reflected
c
           else
             ixx = 2
             s = s - abs((xold-width)*s/(xold2-xold))
c
c     Diffuse reflection
c
             if(ran3(0).gt.specu) then
               eta = 1.5d00 * pi
               theta = asin(sqrt(ran3(0)))
               phi = 2.0d00 * pi * ran3(0)
               rx = -cos(theta)
               ry = sin(theta) * sin(phi)
               rz = sin(theta) * cos(phi)
               call caleta(eta,rx,rz)
c
c     Specular reflection
c
             else
               rx = -rx
               ry = ry
               rz = rz
               eta =2.0d00 * pi - eta
             endif
           endif
         endif
c
c     Does the bundle hit the surface 5 or 6 ?
c
```

```
      elseif(y.lt.0.0d00) then
        call surface5
      elseif(y.gt.alen) then
        call surface6
c
c     The bundle is located in gas
c
      else
        ixx = 3
        call gas
      endif
c
   40 return
      end

c-----------------------------------------------------------------
c   This subroutine calculates the bundle history which hit
c                        the surface 3.
c-----------------------------------------------------------------

      subroutine surface3
c
      include 'com.for'
c
      if(x.lt.0.0d00) then
        xold2 = x
        tau = xold / abs(rx)
        x = 0.0d00
        y = yold + tau * ry
        z = zold + tau * rz
c
        if(y.lt.0.0d00) then
          call surface5
        elseif(y.gt.alen) then
          call surface6
        else
          if(ran3(0).le.abopw) then
            ixx = 1
            do 10 i=1,kz
              if(z.le.hig*i/kz) then
                ni = i
                goto 20
              endif
   10         continue
   20         do 30 j = 1,ky
```

```
              if(y.le.alen*j/ky) then
                ns3(j,ni) = ns3(j,ni) + 1
                goto 40
              endif
   30       continue
c
c     The bundle is reflected
c
          else
            ixx = 2
            s = s - abs(xold*s/(xold2-xold))
c
c     Diffuse reflection
c
            if(ran3(0).gt.specu) then
              eta = pi / 2.0d00
              theta = asin(sqrt(ran3(0)))
              phi = 2.0d00 * pi * ran3(0)
              rx = cos(theta)
              ry = sin(theta) * sin(phi)
              rz = -sin(theta) * cos(phi)
              call caleta(eta,rx,rz)
c
c     Specular reflection
c
            else
              rx = -rx
              ry = ry
              rz = rz
              eta = 2.0d00 * pi - eta
            endif
          endif
        endif
c
c     Does the bundle hit the surface 5 or 6 ?
c
        elseif(y.lt.0.0d00) then
          call surface5
        elseif(y.gt.alen) then
          call surface6
c
c     the bundle is located in gas
c
        else
          ixx = 3
```

```
        call gas
      endif
c
   40 return
      end

c-----------------------------------------------------------------
c   This subroutine calculates the bundle history which hit
c                       the surface 4.
c-----------------------------------------------------------------

      subroutine surface4
c
      include 'com.for'
c
      if(z.gt.hig) then
        zold2 = z
        tau = (hig - zold) / abs(rz)
        x = xold + tau * rx
        y = yold + tau * ry
        z = hig
c
        if(y.lt.0.0d00) then
          call surface5
        elseif(y.gt.alen) then
          call surface6
        else

          if(ran3(0).le.abopw) then
            ixx = 1
            do 10 i=1,kx
              if(x.le.width*i/kx) then
                ni = i
                goto 20
              endif
   10       continue
   20       do 30 j = 1,ky
              if(y.le.alen*j/ky) then
                ns4(ni,j) = ns4(ni,j) + 1
                goto 40
              endif
   30       continue
c
c     The bundle is reflected
c
```

```
          else
            ixx = 2
            s = s-abs((hig-zold)*s/(zold2-zold))
c
c     Diffuse reflection
c
            if(ran3(0).gt.specu) then
              eta = pi
              theta = asin(sqrt(ran3(0)))
              phi = 2.0d00 * pi * ran3(0)
              rx = -sin(theta) * cos(phi)
              ry = sin(theta) * sin(phi)
              rz = - cos(theta)
              call caleta(eta,rx,rz)
c
c     Specular reflection
c
            else
              rx = rx
              ry = ry
              rz = -rz
              if(rx.ge.0.0d00) then
                eta = pi - eta
              else
                eta = 3.0d00 * pi - eta
              endif
            endif
          endif
        endif
c
c     Does the bundle hit the surface 5 or 6 ?
c
      elseif(y.lt.0.0d00) then
        call surface5
      elseif(y.gt.alen) then
        call surface6
c
c     The bundle is located in gas
c
      else
        ixx = 3
        call gas
      endif
c
   40 return
```

```
      end

c-----------------------------------------------------------------
c  This subroutine calculates the bundle history which hit
c                      the surface 5.
c-----------------------------------------------------------------

      subroutine surface5
c
      include 'com.for'
c
      yold2 = y
      tau = yold/abs(ry)
      x = xold + tau * rx
      z = zold + tau * rz
      y = 0.0d00

      if(ran3(0).le.abopw) then
        ixx = 1
        do 10 i = 1,kx
          if(x.le.width*i/kx) then
            ni = i
            goto 20
          endif
   10   continue
   20   do 30 j = 1,kz
          if(z.le.hig*j/kz) then
            ns5(ni,j) = ns5(ni,j) + 1
            goto 40
          endif
   30   continue
      else
        ixx = 2
        s = s - abs(yold*s/(yold2-yold))
        if(ran3(0).gt.specu) then
          theta = asin(sqrt(ran3(0)))
          phi = 2.0d00 * pi * ran3(0)
          rx = sin(theta) * cos(phi)
          ry = cos(theta)
          rz = -sin(theta) * sin(phi)
          call caleta(eta,rx,rz)
        else
          rx = rx
          ry = -ry
          rz = rz
```

```
          eta = eta
        endif
      endif

   40 return
      end

c-----------------------------------------------------------------
c  This subroutine calculates the bundle history which hit
c                    the surface 6.
c-----------------------------------------------------------------

      subroutine surface6
c
      include 'com.for'
c
      yold2 = y
      tau = (alen-yold)/abs(ry)
      x = xold + tau * rx
      z = zold + tau *rz
      y = alen
c
      if(ran3(0).le.abopw) then
        ixx = 1
        do 10 i = 1,kx
          if(x.le.width*i/kx) then
            ni = i
            goto 20
          endif
   10   continue
   20   do 30 j = 1,kz
          if(z.le.hig*j/kz) then
            ns6(ni,j) = ns6(ni,j) + 1
            goto 40
          endif
   30   continue
      else
        ixx = 2
        s = s - abs((yold-alen)*s/(yold2-yold))
        if(ran3(0).gt.specu) then
          theta = asin(sqrt(ran3(0)))
          phi = 2.0d00 * pi * ran3(0)
          rx = - sin(theta) * cos(phi)
          ry = - cos(theta)
          rz = - sin(theta) * sin(phi)
```

```
            call caleta(eta,rx,rz)
          else
            rx = rx
            ry = -ry
            rz = rz
            eta = eta
          endif
        endif

   40 return
      end

c-----------------------------------------------------------------
c    This subroutine caleta calculates new directions based on
c                        X - z coordinate.
c-----------------------------------------------------------------

      subroutine caleta(eta,rx,rz)
      real*8 eta,rx,rz,pi

      pi = 4.0d00 * atan(1.0d00)
c
      if(rx.ge.0.0d00.and.rz.gt.0.0d00) then
        etap = atan(rx/rz)
      elseif(rx.ge.0.0d00.and.rz.eq.0.0d00) then
        etap = pi / 2.0d00
      elseif(rz.le.0.0d00) then
        if(rx.lt.0.0d00.and.rz.eq.0.0d00) then
          etap = 1.5d00 * pi
        else
          etap = pi + atan(rx/rz)
        endif
      else
        etap = 2.0d00 * pi + atan(rx/rz)
      endif
      eta = etap
c
      return
      end

c-----------------------------------------------------------------
c   This function program generates random number.
c
c-----------------------------------------------------------------
```

```
      function ran3(idum)
c
c     implicit real*4(m)
c     parameter (mbig=4000000.,mseed=1618033.,mz=0.,fac=2.5e-7)
c
      implicit real*8 (a-h,o-z)
      parameter (mbig=1000000000,mseed=161803398,mz=0,fac=1.e-9)
      dimension ma(55)
      data iff /0/
      if(idum.lt.0.or.iff.eq.0)then
        iff=1
        mj=mseed-iabs(idum)
        mj=mod(mj,mbig)
        ma(55)=mj
        mk=1
        do 11 i=1,54
          ii=mod(21*i,55)
          ma(ii)=mk
          mk=mj-mk
          if(mk.lt.mz)mk=mk+mbig
          mj=ma(ii)
   11   continue
        do 13 k=1,4
          do 12 i=1,55
            ma(i)=ma(i)-ma(1+mod(i+30,55))
            if(ma(i).lt.mz)ma(i)=ma(i)+mbig
   12     continue
   13   continue
        inext=0
        inextp=31
      endif
      inext=inext+1
      if(inext.eq.56)inext=1
      inextp=inextp+1
      if(inextp.eq.56)inextp=1
      mj=ma(inext)-ma(inextp)
      if(mj.lt.mz)mj=mj+mbig
      ma(inext)=mj
      ran3=mj*fac
      return
      end

c-------------------------------------------------------------------
c  This subroutine calculate new direction of bundles emitted
c          from medium and counts bundle numbers
```

```
c-------------------------------------------------------------------

      subroutine gas
c
      include 'com.for'
c
      pi = 3.141592654
      theta = acos(1.0d00 - 2.0d00 * ran3(0))
      phi = 2.0d00 * pi * ran3(0)
      rx = sin(theta) * cos(phi)
      ry = sin(theta) * sin(phi)
      rz = cos(theta)
c
      call caleta(eta,rx,rz)
c
      do 20 i = 1,kz
        if(z.le.hig*i/kz) then
          ni = i
          goto 25
        endif
   20 continue
   25 do 30 j = 1,ky
        if(y.le.alen*j/ky) then
          nj = j
          goto 40
        endif
   30 continue
   40 do 45 k = 1,kx
        if(x.le.width*k/kx) then
          nsa(k,nj,ni) = nsa(k,nj,ni) + 1
          goto 50
        endif
   45 continue
c
   50 return
      end

c-------------------------------------------------------------------
c   This subroutine read in all information necessarz to perform
c                    the simulation.
c-------------------------------------------------------------------

      subroutine input
c
      include 'com.for'
```

```
c
      open(unit=5,file='input3d.dat',status='old')
c
c     Line 1 : read the dimension of model
c
c       width(real) : width of  enclouser
c       alen(real): length of enclouser
c       hig(real) : hight of  enclouser
c       dia(real) : diameter of the pipe
c       dx(real)  : distance from left of the enclouser to the center
c                   of the pipe
c       dz(real)  : distance from bottom of the enclouser to the center
c                   of the pipe
c
      read(5,*) width,alen,hig,dia,dx,dz
c
c     Line 2
c
c       kx   : number of strip in x-direction
c       ky   : number of strip in y-direction
c       kz   : number of strip in z-direction
c       kp   : number of segment through the circumstance of circle
c       nuemx : number of emitting sources in x direction
c       nuemy : number of emitting sources in y direction
c       npn  : total number of bundles at each emitting source
c
      read(5,*) kx,ky,kz,kp,nuemx,nuemy,npn
c
c     Line 3 : read each properties
c
c       abopw : absorptivitz of walls(Assume that all surfaces except
c               the circle have same surface properties)
c       specu : specularitz of wall surfaces
c       abop  : absorptivitz of circle surface
c
      read(5,*) abopw,specu,abop
c
c     Line 4
c
c       ot  :  optical thickness of media
c
       read(5,*) ot
       close(5)
c
c     Write out setup information of given model
```

```
c
      write(6,2000)
      write(6,2010) width
      write(6,2015) alen
      write(6,2020) hig
      write(6,2030) dia
      write(6,2040) dx
      write(6,2050) dz
      write(6,2060) kx
      write(6,2065) ky
      write(6,2070) kz
      write(6,2080) kp
      write(6,2090) nuemx
      write(6,2095) nuemy
      write(6,2100) npn
      write(6,2110) abopw
      write(6,2120) specu
      write(6,2130) abop
      write(6,2140) ot
c
 2000 format(7x,'Dimension and properties of given model')
 2010 format(7x,'width of rectangular enclouser              :',f7.3)
 2015 format(7x,'length of rectangular enclouser             :',f7.3)
 2020 format(7x,'hight of rectangular enclouser              :',f7.3)
 2030 format(7x,'diameter of the circle                     :',f7.3)
 2040 format(7x,'distance from left of the enclouser to '/
     +   '                    the center of circle       :',f7.3)
 2050 format(7x,'distance from bottom of the enclouser to '/
     +   '                     the center of circle      :',f7.3)
 2060 format(7x,'number of strips in x-direction             :',i4)
 2065 format(7x,'number of strips in y-direction             :',i4)
 2070 format(7x,'number of strips in z-direction             :',i4)
 2080 format(7x,'number of strips in circumstance of circle  :',i4)
 2090 format(7x,'number of emitting sources in x direction   :',i4)
 2095 format(7x,'number of emitting sources in y direction   :',i4)
 2100 format(7x,'number of bundles at each emitting'/
     +   '                                    source     :',i6)
 2110 format(7x,'absorptivitz of walls                      :',f7.3)
 2120 format(7x,'specularitz of wall surfaces               :',f7.3)
 2130 format(7x,'absorptivitz of circle surface             :',f7.3)
 2140 format(7x,'optical thickness of media                 :',f7.3)
c
      return
      end
```

```
c-----------------------------------------------------------------
c              This subroutine print out the results
c-----------------------------------------------------------------

      subroutine output
c
      include 'com.for'
c
      delx = width/kx
      dely = alen/ky
      delz = hig/kz
      totaln = npn * nuemx * nuemy
c
      open(unit=7,file='medium.dat',status='old')
      write(7,*)'This is the distribution of bundle fraction in medium'
      write(7,*)'     ----------------------------------------'
      write(7,*)'          Position              Fraction'
      write(7,*)'          (x,y,z)            N(xyz)/N(total)'
      write(7,*)'     ----------------------------------------'
c      do 200 i=1,kx
c         sum = 0.0d00
c         do 100 j=1,ky
c            do 50 k = 1,kz
c               frac = nsa(i,j,k)/totaln
c               px = width / kx * i - width / 2.0d00 / kx
c               py = alen / ky * j - alen / 2.0d00 / ky
c               pz = hig / kz * k - hig / 2.0d00 / kz
c               sum = sum + frac
c               write(7,1000) px,py,pz,frac
c   50        continue
c            write(7,*)
c  100     continue
c         write(7,1100) i,sum
c         write(7,*)
c  200 continue
      close(7)
c
c
      open(unit=7,file='wall14.dat',status='old')
      write(7,*)'     Distribution of bundle fraction in wall-1,4'
      write(7,*)'  ------------------------------------------------'
      write(7,*)'       Position(y,z)      Wall - 1        Wall - 4'
      write(7,*)'  ------------------------------------------------'
      sum1 = 0.0d00
      sum4 = 0.0d00
```

```
      do 300 i=1,kx
        do 250 j = 1,ky
          fra1 = ns1(i,j)/delx/dely/(totaln/width/alen)
          fra4 = ns4(i,j)/delx/dely/(totaln/width/alen)
          px = width / kx * i
          py = alen / ky * j
          sum1 = sum1 + ns1(i,j)/totaln
          sum4 = sum4 + ns4(i,j)/totaln
          write(7,1200) px,py,fra1,fra4
  250   continue
        write(7,*)
  300 continue
      write(7,1300) sum1,sum4
      close(7)
c
c
      open(unit=7,file='wall23.dat',status='old')
      write(7,*)'    Distribution of bundle fraction in Wall-2,3'
      write(7,*)' ------------------------------------------------'
      write(7,*)'      Position(z)       Wall - 2       Wall - 3'
      write(7,*)' ------------------------------------------------'
      sum2 = 0.0d00
      sum3 = 0.0d00
      do 400 i=1,ky
        do 350 j=1,kz
          fra2 = ns2(i,j)/dely/delz/(totaln/width/alen)
          fra3 = ns3(i,j)/dely/delz/(totaln/width/alen)
          py = alen / ky * i
          pz = hig / kz * j
          sum2 = sum2 + ns2(i,j)/totaln
          sum3 = sum3 + ns3(i,j)/totaln
          write(7,1200) py,pz,fra2,fra3
  350   continue
        write(7,*)
  400 continue
      write(7,1300) sum2,sum3
      close(7)
c
c
      open(unit=7,file='pipe.dat',status='old')
      write(7,*)'      Distribution of bundle fraction in Pipe'
      write(7,*)'      ---------------------------------------'
      write(7,*)'           Position            Fraction'
      write(7,*)'           (y,angle)      N(y,angle)/N(total)'
      write(7,*)'      ---------------------------------------'
```

```
      sum = 0.0d00
      do 500 i=1,ky
        do 450 j=1,kp
          frac = nsp(i,j)/dely/(pi*dia/kp)/(totaln/width/alen)
          py = alen / ky * i
          pd = 360.0d00 / kp * j
          sum = sum + nsp(i,j)/totaln
          write(7,1400) py,pd,frac
 450    continue
        write(7,*)
 500  continue
      write(7,1500) sum
      close(7)
c
      open(unit=7,file='wall56.dat',status='old')
      write(7,*)'     Distribution of bundle fraction in Wall-5,6'
      write(7,*)'  ------------------------------------------------'
      write(7,*)'       Position(x,z)       Wall - 5        Wall - 6'
      write(7,*)'  ------------------------------------------------'
      sum5 = 0.0d00
      sum6 = 0.0d00
      do 510 i=1,kx
        do 510 j=1,kz
         a56(i,j)=0.25d00
 510  continue

      a56(8,8)=0.015
      a56(13,8)=0.015
      a56(8,13)=0.015
      a56(13,13)=0.015
      a56(7,8)=0.209945
      a56(8,7)=0.209945
      a56(13,7)=0.209945
      a56(14,8)=0.209945
      a56(13,14)=0.209945
      a56(14,13)=0.209945
      a56(7,13)=0.209945
      a56(8,14)=0.209945
      a56(7,9)=0.077207
      a56(9,7)=0.077207
      a56(12,7)=0.077207
      a56(14,9)=0.077207
      a56(14,12)=0.077207
      a56(12,14)=0.077207
      a56(7,12)=0.077207
```

```
      a56(9,14)=0.077207
      a56(7,10)=0.00957
      a56(10,7)=0.00957
      a56(7,11)=0.00957
      a56(11,7)=0.00957
      a56(14,10)=0.00957
      a56(14,11)=0.00957
      a56(10,14)=0.00957
      a56(11,14)=0.00957

      do 600 i=1,kx
        do 550 j=1,kz

          fra5 = ns5(i,j)/a56(i,j)/(totaln/width/alen)
          fra6 = ns6(i,j)/a56(i,j)/(totaln/width/alen)
          px = width / kx * i
          pz = hig / kz * j
          sum5 = sum5 + ns5(i,j)/totaln
          sum6 = sum6 + ns6(i,j)/totaln
          write(7,1200) px,pz,fra5,fra6
  550   continue
        write(7,*)
  600 continue
      write(7,1300) sum5,sum6
      close(7)
c
 1000 format(3x,3f7.2,f18.6)
 1100 format('     Total fraction in column(',i3,') : ',f9.6)
 1200 format(4x,2f7.2,2f16.6)
 1300 format('        Total fractions :',f9.6,f16.6)
 1400 format(6x,2f8.2,f20.6)
 1500 format('         Total fraction in pipe : ',f8.6)
c
      write(6,1800) akkk(jk)/10.0,sum,sum4,sum2,sum5
1800  format(2x,f7.2,4f9.5)
      return
      end
c-----------------------------------------------------------------
```

```
c-----------------------------------------------------------------
c                 Cmomon block for hong3d.for
c-----------------------------------------------------------------
      implicit real*8(a-h,o-z)
      integer ns1(30,30),ns2(30,30),ns3(30,30),ns4(30,30),
     +        ns5(30,30),ns6(30,30),nsp(30,36),nsa(30,30,30)
      real*8 a56(20,20),otp(20),akkk(20)
      common /proper/ specu,abopw,abop,ot,absco
      common /bundle/ nuemx,nuemy,npn
      common /locate/ x,y,z,xold,yold,zold,rx,ry,rz,dx,dz,kx,ky,kz,kp
      common /shape/ width,alen,hig,dia
      common /surface/ ixx,ns1,ns2,ns3,ns4,ns5,ns6,nsp,nsa,a56
      common /angle/ pi,s,eta,phi
      common /new/ rxnew,rynew,rznew,otp,akkk,jk
c-----------------------------------------------------------------
```