NUMERICAL INVESTIGATION OF COMBINED RADIATION AND NATURAL CONVECTION HEAT TRANSFER IN A HORIZONTAL ANNULUS

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Abstract Combined radiation and natural convection within the annular ragion of two infinitely long horizontal concentric cylinders are investigated numerically in this research. Radial and tangential radiation effects are considered using Milne-Eddington approximation for a two-dimensional radiative transfer. The basic conservation equations are discretized with the finite volume method and SIMPLER algorithm. The result are presented through velocity vector field, streamline and isothermal plots. It is observed that radiation has significant effect on flow and temperature fields. Results of local Nusselt number prediction along the surface of the inner cylinder show that radiation suppresses the angular dependence of Nusselt number.

Key Words Radiation, Laminar Natural Convection, SIMPLER

چکیده در این مقاله ترکیب انتقال حرارت تشعشعی و جابجایی آزاد در ناحیهٔ حلقوی بین دو استوانه افقی هم مرکز به صورت عددی بررسی شده است. اثرات تشعشع مماسی و شعاعی با استفاده از تقریب میلن - ۱ دینگتون برای تشعشع دو بعدی درنظر گرفته شده است. معادلات اصلی بقا با استفاده از روش احجام محدود و به وسیلهٔ الگوریتم سیمپلر حل شده‌اند. نتایج به صورت میدان بدار سرعت، خطوط جریان و منحنی‌های دما ثابت ارایه شده است. مشاهده شده است که تشعشع اثرات مهمی در جریان و میدان دما دارد. نتایج توزیع عدد ناسلت موضعی روی استوانه داخلی، نشان می‌دهد که افزایش اثرات تشعشع وابستگی عدد ناسلت را به زاویه خنثی می‌کند.

INTRODUCTION

Laminar natural convection heat transfer in a horizontal annulus of two concentric cylinders has been investigated widely due to the various practical applications such as concentrators of solar collectors, electrical transmission cables and cooling of electronic components. Incorporation of radiation in natural convection, especially radiation as a volumetric phenomenon for the case of absorbing and emitting media, makes the case highly nonlinear and complex. Due to the complexities involved in formulating and solving this problem, only few research work has been carried out on this subject [1, 2, 3].

For two-dimensional, laminar buoyancy-induced flow in annulus, results have been established to an extent that this configuration is used as a source of comparison for validating relevant numerical codes [4,5,6]. Experimental studies [4]. Have revealed that there is a critical Rayleigh number below which the convective flow patterns are steady and laminar and above which the transition from laminar to turbulent flow occurs. This Rayleigh number is about 106 for a radius ratio of 2.6 and air as working fluid. Some scholars have also investigated the transition and turbulent natural convection for the geometry of annulus between two concentric cylinders [7,8,9].

The effect of thermal radiation on natural convection can be neglected for low-temperature-level applications. However, high temperature levels exist in many modern technology system and thers is a need to include the radiative effects of the participating fluid as well as of the boundaries. The formulation of radiative transfer equation for cylindrical geometries can be derived in various forms. The cylindrical radiative transfer equation can be expressed in the form of an integro-differential equation that is tedious to solve analytically. Tan and Howell [2] solved the problem of combined radiation and laminar natural convecation in a participating media between horizontal concentric cylinders by the YIX method. This method was used to discretize the exact radiation transport equation of integral form. Their research revealed that radiation has significant influence on the flow and temperature fields, as well as on the heat transfer rate. A simple model based on Milne-Eddington approximation has been used [10,11] to describe thermal radiation in cylindrical geometry, in which a differential equation is obtained for radiative transfer equation. In these papers, the tangential radiation is assumed to be negligible compared with radial direction. In the present work buovancy-induced flow makes the temperature change in the tangential direction and therefore neglecting the tangential component of radiation is not correct. Onyegegbu [1] who made an analytical study on heat transfer inside a horizontal cylindrical annulus in the presence of thermal radiation and buoyancy, used the Milne-Eddington differential approximation in a formulation including tangential radiation. Results obtained by Onyegegbu [1] indicate that decreasing plank number, increasing the degree of nongrayness of the fluid or increasing optical thickness increases the total heat transfer and reduces the induced buoyant flow intensity and velocity. Also it is reported that because radiation decreases fluid effective Prandtl number, increasing radiation causes a downward movement of the center of the eddy formed with medium Prandtl number fluids like air [1].

To the best of author's knowledge the works of Onyegegbu [1] and Tan and Howell [2] are the only reported theoretical results pertinent to the combined radiation and natural convection in an annular geometry. In this paper, a numerical study is carried out for the problem of combined radiation and natural convection in participating media between two concentric cylinders. A two-dimensional cylindrical coordinate is used in formulating the basic conservation equations including the radiation transfer equation in radial and tangential directions. The distinguishing feature of the present investigation is the numerical method used for the solution of the problem, which is based on SIMPLER algorithm [12] and investigation of the effect of radius ratio and Rayleigh number on radiative and total heat fluxes.

FORMULATION

The geometry of the two-dimensional annular gap between two horizontal concentric cylinders of radii R_i (inner cylinder) and R_0 (outer cylinder) is shown in Fig. 1. The cylindrical polar coordinates system, r and θ, as used in formulation of the problem. The angular position is measured from the bottom of the annulus in the counter-clockwise direction. The computational domain is bounded by $0 \leq \theta \leq \pi$ due to the symmetry about the vertical diameter.

Considering an absorbing and emitting nongray Boussinesq fluid in the annular gap between two horizontal concentric cylinders, the basic conservation equations of mass,

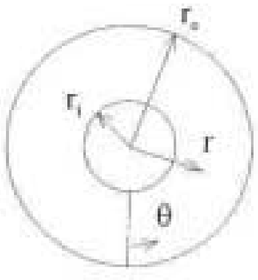


Figure 1. Geometry of annular gap.

momentum and energy can be expressed in polar coordinate as follows.

Continuity:

$$\frac{\partial V}{\partial r} + \frac{1}{r}\frac{\partial U}{\partial \theta} + \frac{V}{r} = 0 \tag{1}$$

θ momentum:

$$\rho\left[V\frac{\partial U}{\partial r} + \frac{U}{r}\frac{\partial U}{\partial \theta}\right] = -\frac{1}{r}\frac{\partial P}{\partial \theta} - \rho\frac{UV}{r} + \mu\left[\frac{\partial^2 U}{\partial r^2} + \frac{1}{r}\frac{\partial U}{\partial r} + \frac{1}{r^2}\frac{\partial^2 U}{\partial \theta^2} - \frac{U}{r^2} - \frac{2}{r^2}\frac{\partial V}{\partial \theta}\right] - \rho g\left\{1-\beta\left[T-T_0\right]\right\}\sin\theta \tag{2}$$

r momentum:

$$\rho\left[V\frac{\partial V}{\partial r} + \frac{U}{r}\frac{\partial V}{\partial \theta}\right] = -\frac{\partial P}{\partial r} + \rho\frac{U^2}{r} + \mu\left[\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2} - \frac{V}{r^2} - \frac{2}{r^2}\frac{\partial U}{\partial \theta}\right] + \rho g\left\{1-\beta\left[T-T_0\right]\right\}\cos\theta \tag{3}$$

Energy:

$$\rho C_p\left[V\frac{\partial T}{\partial r} + \frac{U}{r}\frac{\partial T}{\partial \theta}\right] = K\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}\right] + \nabla\cdot\vec{q}^R \tag{4}$$

The energy equation contains an additional term due to the radiative heat flux vector, $\vec{q}^R$. In two-dimensions, this variable has two components, a radial component, q_r^R, and a tangential component, q_θ^R. These quantities can be obtained from the radiative transfer equation in gases with the assumption of local isotropy for radiative intensity, which is the Milne-Eddington approximation. The radiative transfer equation for gases written in cylindrical coordinates is:

$$\cos\phi\frac{\partial I_\lambda}{\partial r} + \frac{\sin\phi\cos\gamma}{r}\frac{\partial I_\lambda}{\partial \theta} = \alpha_\lambda\left[B_\lambda - I_\lambda\right] \tag{5}$$

Where ϕ is the angle between the ray and the radial direction and γ is the azimuth angle such that $\sin\phi\ \cos\gamma$ is the tangential component of the unit vector in a ray direction. Integration of eq. (5) over all solid angles and frequencies gives the required equation for radiative transfer quantity as:

$$\frac{\partial q_r^R}{\partial r} + \frac{1}{r}\frac{\partial q_\theta^R}{\partial \theta} = 4\alpha_p\sigma T^4 - \alpha_E J \tag{6}$$

where J is the hemispherical total radiation intensity defined as:

$$J = \int_0^\infty \int_0^{2\pi} \int_0^\pi I_\lambda \sin\phi\, d\phi\, d\gamma\, d\lambda \tag{7}$$

Multiplying equation (5) by $\cos\phi$ and integrating over all solid angles and frequencies, with the assumption of local isotropy of radiation intensity (I_γ independent of ϕ and γ), gives an equation for q_r^R as follow [1]:

$$\frac{1}{3}\frac{\partial J}{\partial r} = -\alpha_R q_r^R \tag{8}$$

An equation for q_θ^R can be obtained in the same manner by multiplying equation (5) by $\sin\phi\ \cos\gamma$ and integrating over all solid angles and frequencies as:

$$\frac{1}{3}\frac{\partial J}{\partial \theta} = -\alpha_R q_\theta^R \tag{9}$$

Substitution of equations (8) and (9) to equation (6) the radiative transfer equations takes the form:

$$\frac{\partial^2 J}{\partial r^2} + \frac{1}{r}\frac{\partial J}{\partial r} + \frac{1}{r^2}\frac{\partial^2 J}{\partial \theta^2} = 3\alpha_p\,\alpha_R\left[J - 4\sigma T^4\right] \tag{10}$$

The above mentioned equations may be written in nondimensional form by introducing the following dimensionless variables:

$$U^* = \frac{r_i U}{k} \qquad V^* = \frac{r_i V}{k} \qquad r^* = \frac{r}{r_i}$$

$$T^* = \frac{T - T_0}{T_i - T_0} \qquad J^* = \frac{J}{12\sigma T_i^3\left[T_i - T_0\right]}$$

The conservation equations along with the radiative transfer equations in nondimensional forms are as follows:

Continuity:

$$\left[\frac{\partial V^*}{\partial r^*}+\frac{1}{r}\frac{\partial U^*}{\partial \theta}+\frac{V^*}{r^*}\right]=0 \tag{11}$$

θ momentum:

$$\left[V^*\frac{\partial U^*}{\partial r^*}+\frac{U^*}{r^*}\frac{\partial U^*}{\partial \theta}\right]=-\frac{1}{r^*}\frac{\partial P}{\partial \theta}--\frac{U^*V^*}{r}+$$
$$Pr\left[\frac{\partial^2 U^*}{\partial r^{*2}}+\frac{1}{r^*}\frac{\partial U^*}{\partial r^*}+\frac{1}{r^{*2}}\frac{\partial^2 U^*}{\partial \theta^2}-\frac{U^*}{r^{*2}}+\frac{2}{r^{*2}}\frac{\partial V^*}{\partial \theta}\right]+$$
$$Pr.Ra.T^* sin\theta \tag{12}$$

r momentum:

$$\left[V^*\frac{\partial V^*}{\partial r^*}+\frac{U^*}{r^*}\frac{\partial V^*}{\partial \theta}\right]=-\frac{\partial P}{\partial r^*}+\rho\frac{U^{*2}}{r^*}+$$
$$Pr\left[\frac{\partial^2 V^*}{\partial r^{*2}}+\frac{1}{r^*}\frac{\partial V^*}{\partial \theta^*}+\frac{1}{r^{*2}}\frac{\partial^2 V^*}{\partial \theta^2}-\frac{V^*}{r^{*2}}-\frac{2}{r^{*2}}\frac{\partial U^*}{\partial \theta}\right]$$
$$-Pr.Ra.T^* cos\theta \tag{13}$$

energy:

$$\left[V^*\frac{\partial T^*}{\partial r^*}+\frac{U^*}{r^*}\frac{\partial T^*}{\partial \theta}\right]=\left[\frac{\partial^2 T^*}{\partial r^{*2}}+\frac{1}{r^*}\frac{\partial T^*}{\partial r^*}+\frac{1}{r^{*2}}\frac{\partial^2 T^*}{\partial \theta^2}\right]+\frac{\eta}{P1}\nabla^2 J \tag{14}$$

The radiative transfer equation becomes:

$$\nabla^2 J-3\tau^2 J=-\tau^2\left[\frac{1}{1-T'}\right]\left\{T'+(1-T')\,T^*\right\}^4 \tag{15}$$

where τ is optical thickness defined as $\alpha_m r_i$ and T' is temperature ratio of outer cylinder to inner cylinder. The dimensionless boundary conditions are readily determined as follows:

$U^*=V^*=0 \quad at \quad r^*=1,R$

$T^*=1 \quad at \quad r^*=1 \quad and \quad T^*=0 \quad at \quad r^*=R$

The symmetric boundary condition for temperature and velocity occur at $\theta=0$ and $\theta=\pi$:

$$\frac{\partial U^*}{\partial \theta}=\frac{\partial T^*}{\partial \theta}=0 \quad at \quad \theta=0,\pi$$

The corresponding radiative boundary conditions are [12] :

$$J^*=\frac{\eta}{3\chi\tau}\frac{\partial J^*}{\partial r^*}+\frac{1}{3\,(1-T')} \quad at \quad r^*=1$$

$$J^*=\frac{\eta}{3\chi\tau}\frac{\partial J^*}{\partial r^*}+\frac{T'^4}{3\,(1-T')} \quad at \quad r^*=R$$

$$\frac{\partial J^*}{\partial \theta}=0 \quad at \quad \theta=0,\ \pi$$

where

$$\chi=\frac{\varepsilon}{2\,(2-\varepsilon)}$$

and ε is the hemispherical emissivity of the boundary.

COMPUTATIONAL DETAILS

The basic conservation equations of mass, momentum and energy are discretized using finite volume method. Convective and diffusive terms are discretized by power law scheme of Patankar [13]. A staggered grid arrangement is used for velocity components while other variables are computed for the main grid points. The solution algorithm is based on SIMPLER algorithm [13]. The discretized equations were solved using a line by line method along with tridiagonal matrix algorithm, TDMA.

Selection of the number of grid points used in the present computations can be reasoned on the basis of total Nusselt number prediction along the inner cylinder. Results of total Nusselt number prediction along the inner cylinder are shown in Figure 2 for $R_a=10^3$ and Pl=0.1 . The effect of three different grid points is observed in this Figure. Nusselt number prediction for 50×30 grid points nearly corresponds to that obtained from 70×50, while its difference of from that 30×20 grid is remarkable. Based on the observation from this figure, it is concluded that a 50×30 grid system seems to be an appropriate selection for the number of grid points.

Under-relaxation factors used for the present computations depend strongly on the values of Rayleigh and Plank numbers. It varies from 0.5

for low values of Rayleigh and Plank number to 0.9 for high values of these two variables. Convergence was assumed to have been reached when the maximum of residuals for mass, momentum and energy was 0.001. The maximum number of iterations required for convergence range from 1500 for high Rayleigh number to 400 for low Rayleigh number.

RESULTS AND DISCUSSION

The results are presented in two parts. In the first part, results obtained from combined radiation and natural convection are compared with the previously published data to validate the numerical procedure used in the present computation. In the second part, the effect of radiation is discussed on flow and temperature fields and Nusselt number distribution for a radius ratio of 2.6.

Onyegegbu [1] made a numerical computation for combined radiation and natural convection for radius ratio of 1.2 . Figure 3(a) and (b) show angular and radial velocity components at 30 and 120 degrees respectively in the radial

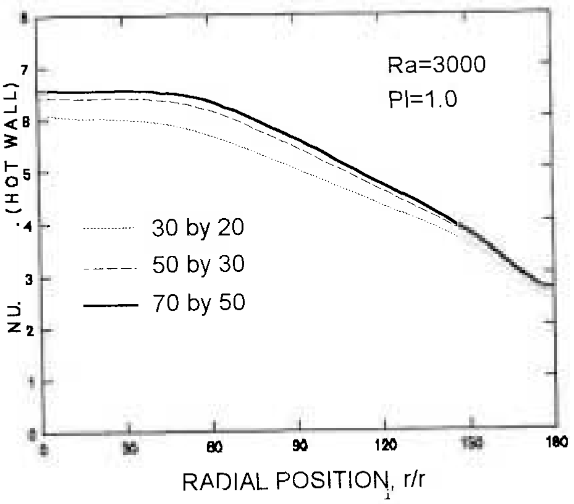


Figure 2. Variation of total Nusselt number along the inner cylinder with the number of grid points.

position at Ra=6×10^6 compared with the results of Onyegegbu [1] . As is observed from this figure, there is a good agreement between the present results and those of [1]. The selection of pl=1.0 in this figure is due to the possibility of comparison with [1]. This number also indicates that the convection and radiation modes of heat transfer are of equal importance in these results.

Results of temperature distribution in the radial direction in 30 and 120 degrees are shown in Figure 3(c). Comparison of results with those of [1] shows that there are good agreements between the present computations and previously published data. In other words, it is demonstrated that the solution of energy equation is correct and can be used for other computations.

After ensuring the accuracy of the computer program, the problem of combined radiation and natural convection is studied in an annular region with the radius ratio of 2.6 . Streamlines and temperature contours for different Rayleigh number and Plank number are shown in Figs. 3-5. with (a) Pl=100 (pure convection), (b) Pl=1.0, (c) Pl=0.1 and (d) Pl=0.01 (convection induced by radiation). These figures are prepared for Rayleigh numbers of 5×10^2, 3×10^3 and 5×10^4 respectively. As is discussed by Kuehn and Goldestin [4], heat transfer can be considered as pure conduction for Rayleigh numbers less than 1000 due to very low velocities associated with natural convection. Therefore the flow and temperature fields observed in Figure 3, can be regarded as representative of the effect of radiation on conduction. In four parts of Figure 3, no significant change is observed in the streamline patterns, except a slight downward movement of the center of rotation. This behavior is also observed in Figure 4. Tan and Howell [2] also reported such a behavior. On the other hand, temperature contours are more dense in radial direction in lower Plank numbers. When Pl=0.01, convection and diffusion of heat are negligible compared with radiation and temperature profiles determined by radiation equation only, so there is a temperature slip on the wall.

An interesting result observed from Fig. 6 is the influence of radiation on flow and temperature distribution at high Rayleigh numbers. As previously mentioned, decreasing Plank number that is equivalent to increasing radiation effects, lowers the center of recirculation region for low Rayleigh numbers. However, the effect of increasing Plank number in Ra=5×10^4 can be explained as instability of the flow pattern in such a way that the single recirculating zone changes to two recirculation regions.

To observe the effect of radiation on flow and temperature distribution more accurately, tangential velocity and temperature distribution in the radial direction are plotted for various Plank numbers for θ=90 deg. in Figure 7.

Although the velocity curves in Figure 7a are the same qualitatively, there are differences in the maximum and minimum values for different Plank numbers. Higher Plank numbers cause higher maximum and minimum values for tangential velocity and lower values for temperature distribution in the annulus.

The next parameter of importance in thermal design problems is the distribution of local Nusselt number along the inner and outer surfaces of the cylinders. To verify the accuracy, first the results are compared with available

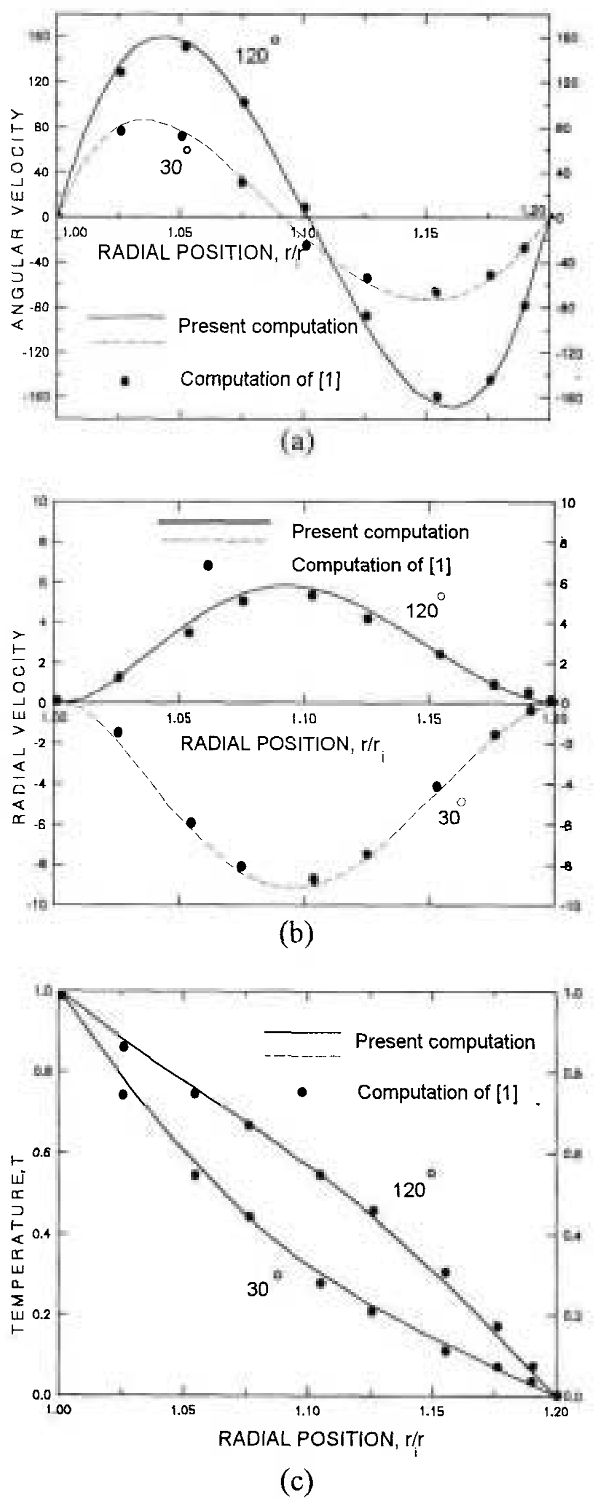


Figure 3. (a) Tangential velocity, (b) radial velocity and (c) temperature distribution for Pl=1.0, τ=1.0, ε=1.0 and Ra=6×10^5.

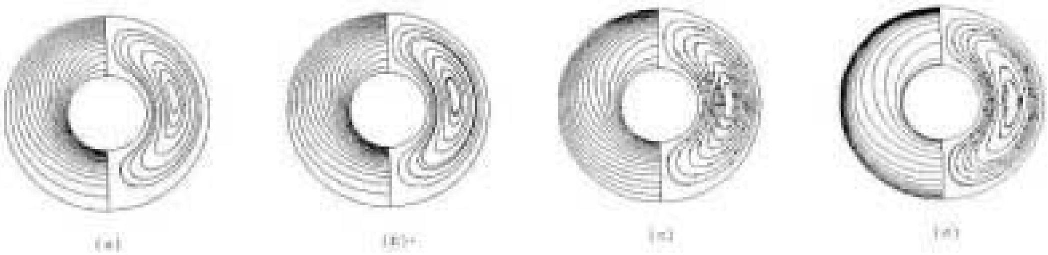


Figure 4. Streamline and temperature contours for Ra=5×10^2 and R=2.6 for (a) Pl=100, (b) Pl=1.0, (c) Pl=0.1, (d) Pl=0.01

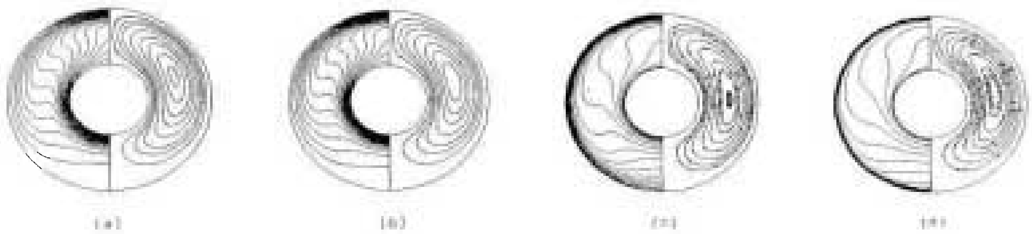


Figure 5. Streamline and temperature contours for Ra=3×10^3 and R=2.6 for (a) Pl=100, (b) Pl=1.0, (c) Pl=0.1, (d) Pl=0.01

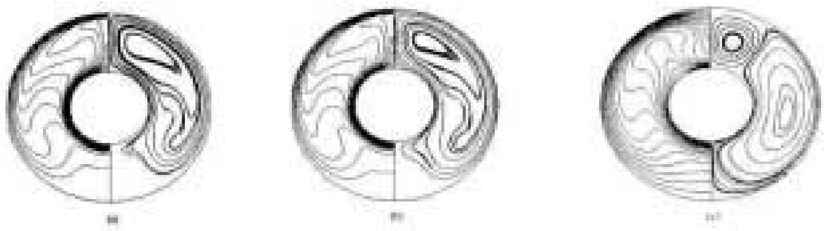


Figure 6. Streamline and temperature contours for Ra=5×10^4 and R=2.6 for (a) Pl=100, (b) Pl=1.0, (c) Pl=0.1

solutions. Figure 8. shows Nusselt number distribution along the tangential direction for Ra=6×10^5 , R=1.2 and Pl=1.0, compared with the results of Onyegegbu [1]. Fair agreement is observed for angles less than 160 degrees. In the last 20 degrees, there is some oscillation in Nusselt number prediction for this radius ratio. This is due to secondary flows at the top of the annulus for this Rayleigh number. Onyegegbu [1] did not observe such a secondary flow, while Powe *et al.* [14] reported such flows at the top of the cylinder for Ra=4.5×10^5 and radius ratio 1.2 such a secondary flow and oscillation in Nusselt number is not observed in higher radius ratio. So it seems that the results reposted by Onyegegbu [1] have some uncertainty in angles from 160 to 180 degrees.

The influence of radiation on total Nusselt number (radiation and convection) is shown in Figure 9 for inner and outer cylinders. In this figure, the vertical axis is Nu_i.Pl/(Pl+1). The reason for choosing the scale Pl/(Pl+1) for the total Nusselt number curve is the possibility of showing Nu_t in a relatively wide range of Plank numbers from 0.001 to 100. Although this curve shows a decrease and smoothness in $Nu_t.Pl/(Pl+1)$ with decreasing Plank number, this does not mean that total Nusselt number decreases with decreasing Plank number. As is deduced from this figure, in fact, decreasing Plank number or increasing the effect of radiation, increases combined Nusselt number. An important result concerning the effect of radiation on natural convection can be deduced from this figure, thta is increasing the effect of radiation (decreasing Plank number) causes the total Nusselt number to attain a more uniform distribution independent of angular position. This result was also reported by Tan and Howell [2].

The effect of radiation on percentage of radiative flux is observed in Figure 10. As is expected, decreasing Plank number or increasing radiation effect increases the percentage of radiative flux such that the angular position dependency almost disappears. In other words, at very low Plank number, the buoyancy-induced flow has a very low effect on heat flux characteristics of the cylinders.

Figure 11. shows the effect of radiation on percent of radiation Nusselt number, Figure 10a and total Nusselt number, Figure 11b for inner and outer cylinders. For Plank numbers greater than 1, the effect of radiation on percent of radiation Nusselt number is negligible, especially for the outer cylinder (cold wall). Its effect is significant for $Pl<0.01$, especially for the inner cylinder. In Figure 11b, the vertical axis is $Nu_t.Pl/(Pl+1)$ as exists in Figure 8.

Although this curve shows increasing in $Nu_t.Pl/(Pl+1)$ with increase in Plank number, this does not mean that total Nusselt number

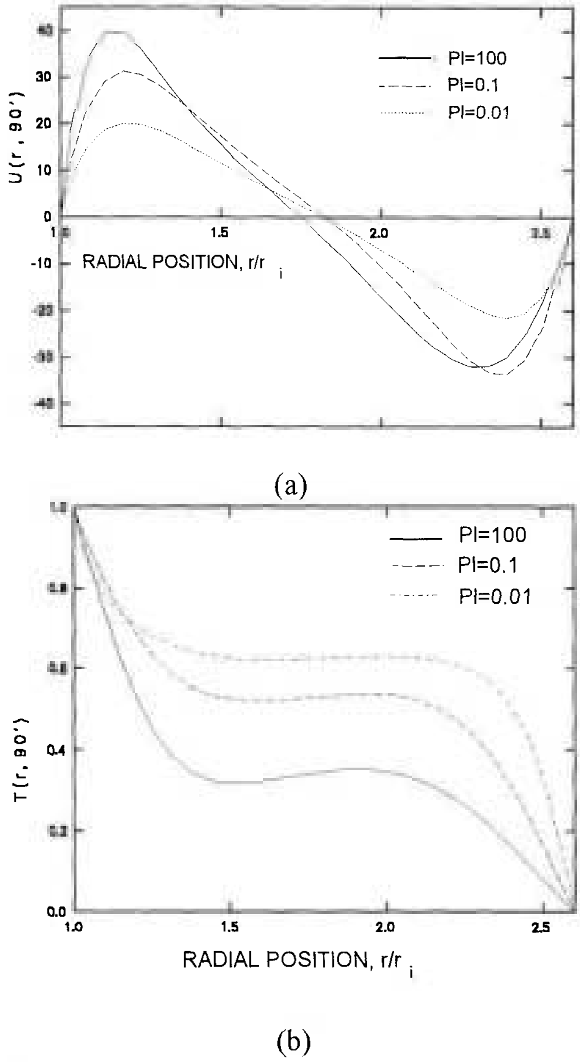
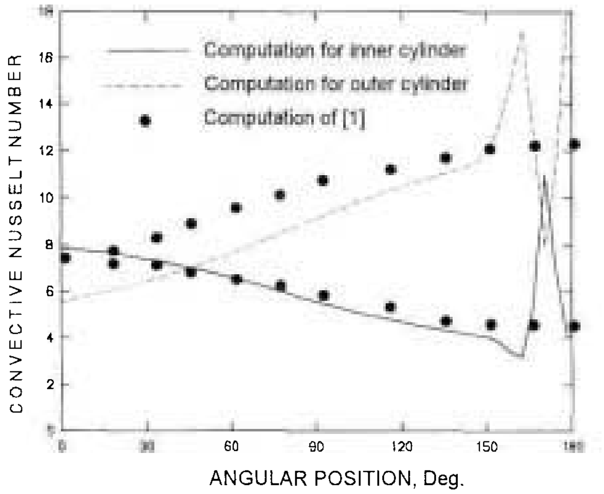


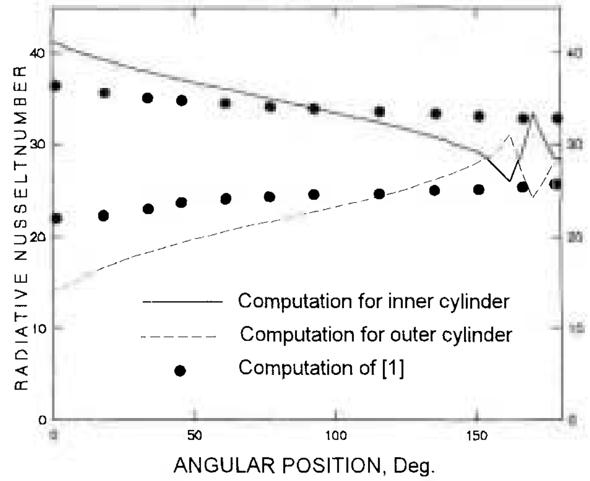
Figure 7. (a) Tangential velocity and (b) temperature distribution in the radial direction for $Pl=0.01$, 0.1 and 100 at $\theta=90$ deg.

increases with increasing Plank number. In fact, the curve of Figure 11b. shows an increase in total Nusselt number with decreasing Plank number.

In this study, the only geometrical parameter which affects the heat transfer rate is radius ratio of two cylinders. Figure 12. shows the effect of radius ratio on radiation and total Nusselt numbers. Figure 12a represents

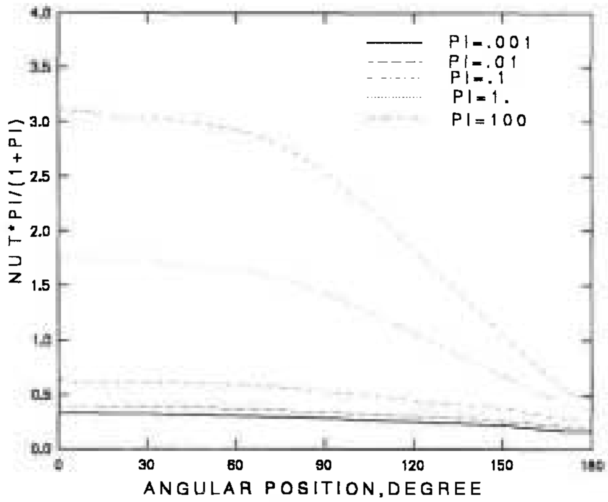


(a)

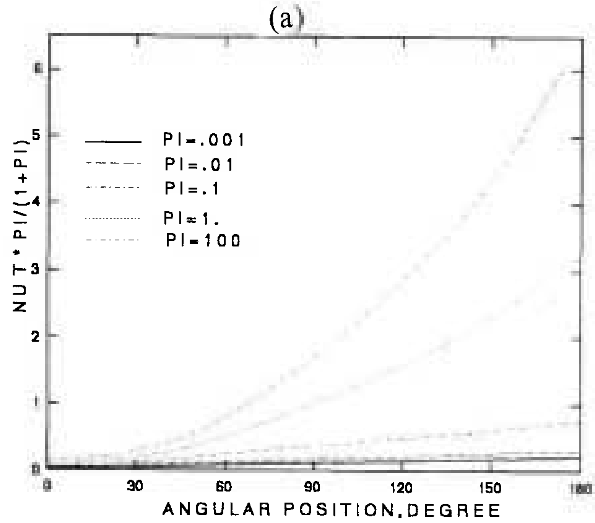


(b)

Figure 8. (a) Convective and (b) radiative Nusselt number distribution along the inner and outer cylinder surfaces at Ra=6×10^5 , R=1.2 and Pl=1.0



(a)



(b)

Figure 9. Effect of radiation on combined Nusselt number for (a) inner and (b) outer cylinders in the angular position

radiation Nusselt number for inner and outer cylinders. As is observed in this figure, increasing the distance between two cylinders makes Nu_r decrease for the outer cylinder and nearly unchanged for inner cylinder.

The effect of radius ratio on total Nusselt number is interesting in this respect that its value decreases to R=1.5 and after that a nearly constant value is attained.

The effect of Rayleigh number on radiation and total Nusselt number is shown in Figure 13 for R=2.6 and Pl=1.0 . It is observed that variation of Rayleigh number has less significance for radiation Nusselt number, Figure 13a, while its effect on total Nusselt number is clearly distinguishable. This behavior is natural due to the fact that as previously

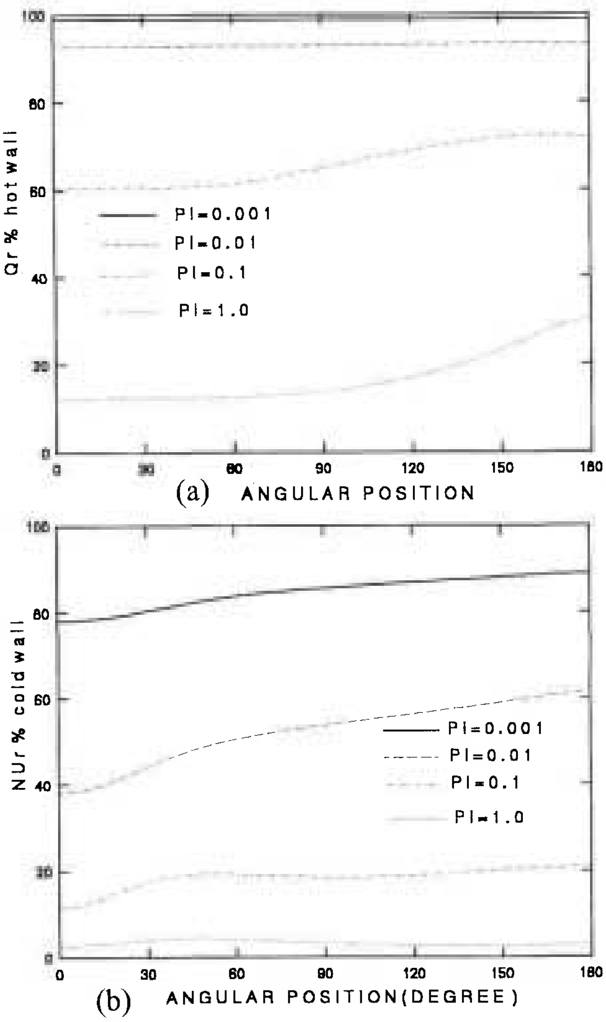


Figure 10. Effect of radiation on percent of radiation Nusselt number for (a) inner and (b) outer cylinders for Ra=3×10^3 and R=1.2

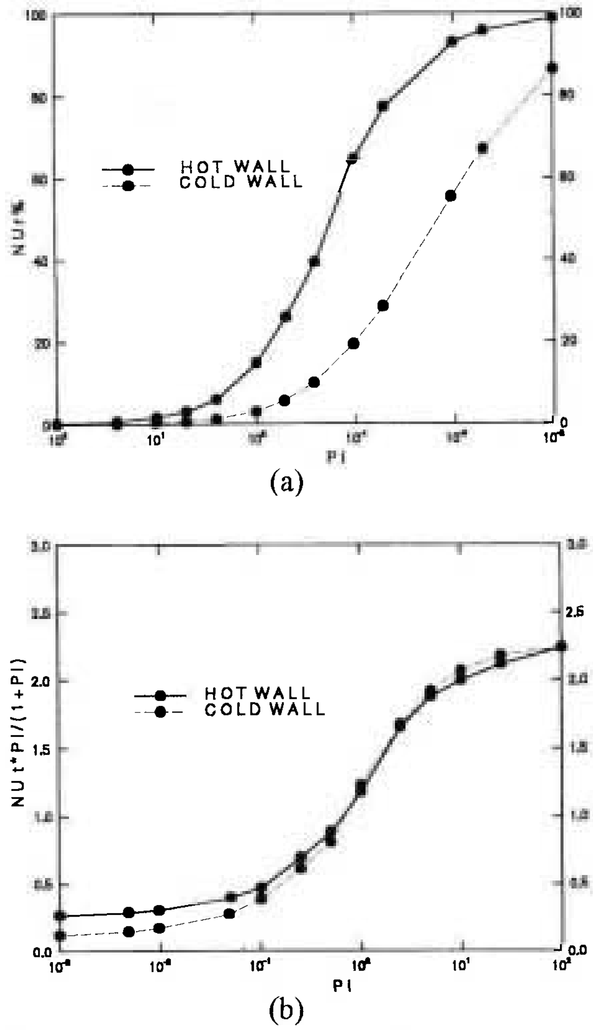


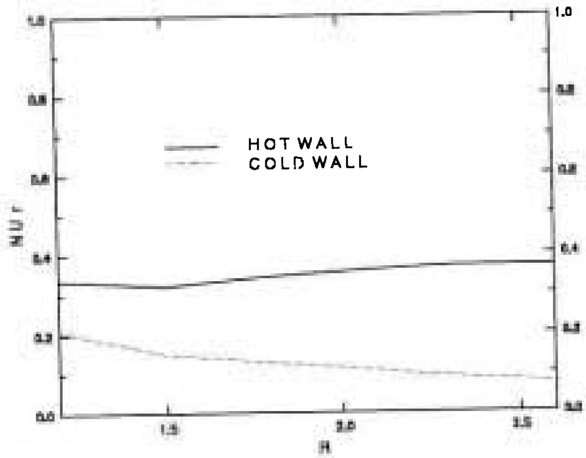
Figure 11. (a) Percent of radiation Nusselt number and (b) total Nusselt number for inner and outer cylinders for Ra=3×10^3 and R=1.2 for various Plank numbers.

mentioned, Rayleigh number variation shows its effect on natural convection and on convection part of the total Nusselt number.

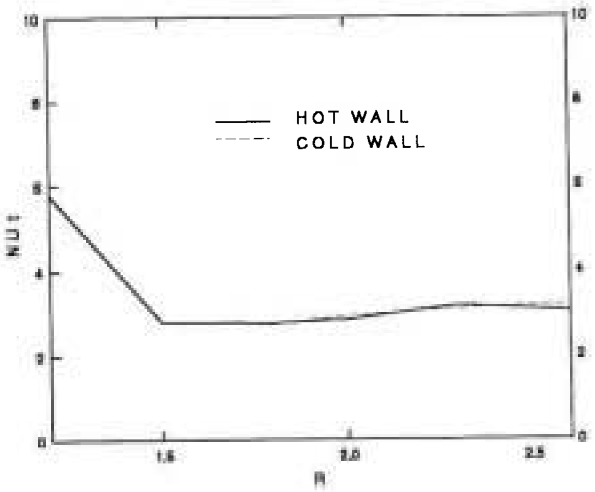
CONCLUSION

In this paper, the problem of combined radiation and natural convection heat transfer inside the annulus region of two horizontal concentric cylinders is studied numerically. The radiative transfer equation along with the basic conservation equations are solved simultaneously. Results obtained from this study can be stated as follows:

1. Thermal radiation affects the flow and temperature fields in natural convection significantly, especially in high Rayleigh numbers. Increasing radiation effects make the flow center of rotation get closer to the horizontal symmetrical line (θ=90) and temperature distribution flatter in the tangential direction.



(a)

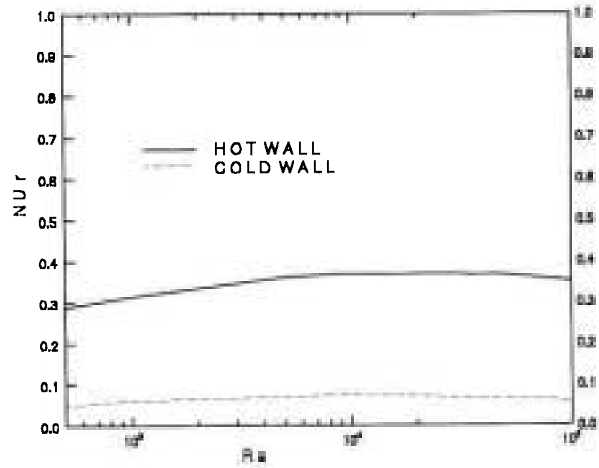


(b)

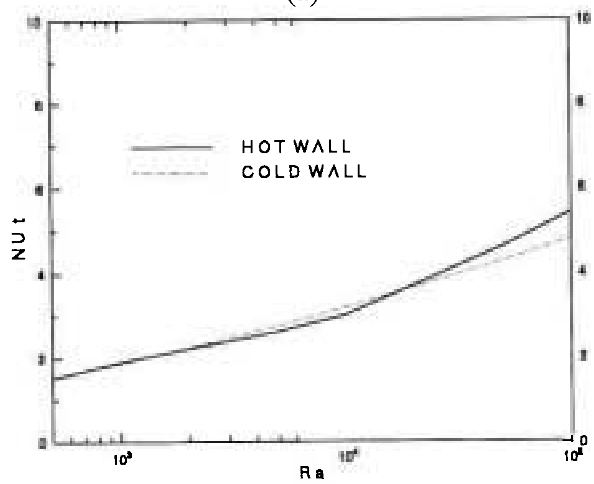
Figure 12. Variation of (a) radiation Nusselt number and (b) total Nusselt number for inner and outer cylinders for $Ra=3\times10^3$ and $P1=1.0$ in radial direction

In high Rayleigh numbers, increasing radiation effect leads the flow pattern to more than one recirculation bubble.

2. In heat transfer, radiation supressed natural convection for Plank numbers as slightly as less than 0.01 . In some cases, more than 90% of heat transfer between these two cylinders is done in radiative mode.



(a)



(b)

Figure 13. Variation of (a) radiation Nusselt number and (b) total Nusselt number for inner and outer cylinders for $R=2.6$ and $P1=1.0$ for various Rayleigh number

3. Radiation Nusselt number for inner and outer cylinders, does not change appreciably with radius ratio and Rayleigh numbers.

NOMENCLATURE

Cp	specific heat at constant pressure
g	acceleration due to gravity
J	radiative intensity
K	thermal conductivity
Nu	local Nusselt number

Nu average Nusselt number
P pressure
P1 Planck number, α_m k/4σT^3_i
Pr Prandtl number,ν /k
r radial position
R radius ratio, r_o/r_i
Ra Rayleigh number, $g\beta$ (T_i-T_o) $r_i^3/k\nu$
T Temperature
τ optical thickness , α_m r_i
β coefficient of thermal expansion
ε hemispherical emissivity of the boundary
η degree of nongrayness of fluid $(\alpha_p/a_R)^{1/2}$
θ angular position
k thermal diffusivity
ν kinematic viscosity
μ dynamic viscosity
ρ fluid density
σ Stefan-Boltzman constant
T$'$ Temperature ratio T_o/T_i
U radial velocity
V tangential velocity

Greek symbols

α_m mean absorption coefficient, $(\alpha_p\ \alpha_R)^{1/2}$
α_p Planck mean absorption coefficient
α_R Rosseland mean absorbtion
α_E Einstein mean absorption coefficient

Subscript

i inner boundary
o outer boundary
ci convective quantity on inner cylinder
ri radiative quantity on inner cylinder
co convective quantity on outer cylinder
ro radiative quantity on outer cylinder

Superscript

* nondimensional quantity

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