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Convection of Radiating Gas in a Vertical Channel through Porous Media

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Abstract

The free convection flow of radiating gas between two vertical thermally conducting walls through porous medium in the presence of a uniform gravitational field has been studied. Closed form solutions for the velocity and temperature have been obtained in the optically thin limit case when the wall temperatures are varying linearly with the vertical distance. It is observed that the fluid velocity increases and the temperature difference between the walls and the fluid decreases with an increase in the radiation parameter. It is also observed that both the fluid velocity and temperature in the flow field increase with an increase in the porosity parameter. It is found that the fluid velocity decreases while the temperature increases with an increase in the thermal conductance of the walls. Further, it is found that radiation causes to decrease the rate of heat transfer to the fluid, thereby reducing the effect of natural convection.

Keywords: Radiation, Porous Medium, Heat Transfer and Thermal Conductance

1. Introduction

In recent years, free convection flow of viscous fluids through porous medium has attracted the attention of a number of researchers in view of its wide application to geophysics, astrophysics, meteorology, aerodynamics, boundary layer control and so on. In addition, convective flow through a porous medium has the application in the field of chemical engineering for filtration and purification processes. In petroleum technology, to study the movement of natural gas oil and water through oil channels/reservoirs and in the field of agriculture engineering to study the underground resources, the channel flows through porous medium have numerous engineering and geophysical applications. However, these studies are confined to normal temperatures of the surrounding medium. If the temperature of the surrounding fluid is rather high, radiation effects play an important role and this situation does exist in space technology. In such cases, one has to take into account the effects of radiation and free convection. Channels are frequently used in various applications in designing ventilating and heating of buildings, cooling electronic components, drying several types of agriculture products grain and food, and packed bed thermal storage. Convective flows in channels driven by temperature differences at bounding walls have been studied and reported extensively in literature. Radiative convective flows are frequently encountered in many scientific and environmental processes such as astrophysical flows, water evaporation from open reservoirs, heating and cooling of chambers and solar power technology. Several researchers have investigated convective flow in porous medium such as Nield and Bejan [1], Sparrow and Cess [2], Burmeister [3], Bejan [4], Kaviany [5] and Vafai [6]. Raptis [7,8] has studied the effect of radiation on free convection flow through a porous medium. The natural convection cooling of vertical rectangular channels in air considering radiation and wall conduction has been studied by Hall *et al*. [9]. Al-Nimr and Haddad [10] have described the fully developed free convection in open-ended vertical channels partially filled with porous material. Thermal dispersion-radiation effects on non-Darcy natural convection in a fluid saturated porous medium have been investigated by Mohammadein and El-Amin [11]. The effect of wall conductances on free convection between asymmetrically heated vertical plates has been studied by Kim *et al*. [12]. Greif *et al*. [13] have made an analysis on the laminar convection of a radiating gas in a vertical channel. Effect of wall conductances on convective magnetohydrodynamic channel flow has been investigated by Yu and Yang [14]. Gupta and Gupta [16] have studied the radiation effect on hydromagnetic convection in a vertical channel. Datta and Jana [15] have studied the effect of wall conductances on hydromagnetic convection of a radiation gas in a vertical channel. Makinde and Mhone [17] investigated the effect of thermal radiation on MHD oscillatory flow in a channel filled with saturated porous medium and non-uniform wall temperatures. Narahari [18] has investiagted the effects of thermal radiation and free convection currents on the unsteady Couette flow between two vertical parallel plates with constant heat flux at one boundary.

In this paper, we have studied the fully developed free convection flow of radiating gas between two vertical thermally conducting walls embedded in porous medium. The governing equations are solved analytically. The effects of the permeability of the porous medium and the influences of radiation parameter and thermal wall conductances on velocity filed and temperature distribution are investigated and analyzed with the help of their graphical representations. It is observed that the fluid velocity $u_1(\eta)$ increases whereas the temperature distribution $\theta(\eta)$ decreases with an increase in the radiation parameter F. It is also observed that both the fluid velocity $u_1(\eta)$ and temperature $\theta(\eta)$ in the flow field increase with an increase in the porosity parameter σ. It is found that the fluid velocity decreases while the temperature increases with an increase in the thermal conductance ψ. Further, it is found that radiation causes to decrease the rate of heat transport to the fluid thereby reducing the effect of natural convection. The rate of flow increases with an increase in either radiation parameter F or Rayleigh number

2. Formulation of the Problem and Its Solutions

Consider a fully developed flow of a viscous incompressible fluid flow in a vertical channel embedded in porous medium. The distance between the channel walls is $2L$. Employ a Cartesian coordinates system with z-axis vertically upwards along the direction of flow and y-axis perpendicular to it. The origin of the axes is such that the channel walls are at positions $y = -L$ and $y = L$ (see **Figure 1**).

For the fully developed laminar flow in porous medium, the velocity and the temperature field have only a vertical component and all of the physical variables except temperature and pressure are functions of y. The temperature inside the fluid can be written as

$$T = T^*(y) + Nz, \tag{1}$$

where N is the vertical temperature gradient.

On the use of (1), the momentum and energy equations are simplified to the following form

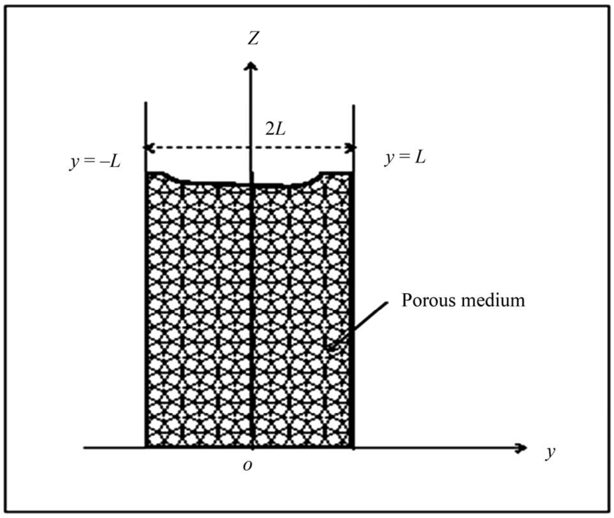

Figure 1. Geometry of the problem.

$$\nu \frac{\mathrm{d}^2 u}{\mathrm{d}y^2} - \frac{\nu}{k'} u + g\beta\left(\theta^* + Nz\right) - \frac{1}{\rho}\frac{\partial p}{\partial z} = 0, \tag{2}$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial z} = 0, \tag{3}$$

$$Nu = \alpha \frac{\mathrm{d}^2 \theta^*}{\mathrm{d}y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}, \tag{4}$$

where $\theta^* = T - T_{w_0}$, ν is the kinematic coefficient of fluid viscosity, g the acceleration due to gravity, k permeability of the porous medium and α the thermal conductivity.

In the optically thin limit, the fluid does not absorb its own emitted radiation. This means that there is no self-absorption but the fluid does absorb radiation emitted by the boundaries. Cogley *et al.* [19] showed that in the optically thin limit for a non-grey gas near equilibrium, the following relation holds

$$\frac{\partial q_r}{\partial y} = 4\left(T - T_w\right)\int_0^\infty K_{\lambda_w}\left(\frac{\partial e_{\lambda h}}{\partial T}\right)_w \mathrm{d}\lambda, \tag{5}$$

where K_λ, is the absorption coefficient, $e_{\lambda h}$ is the Planck function and the subscript w refers to values at the wall. Further simplifications can be made concerning the spectral properties of radiating gases ([20]) but are not necessary for our investigation.

On the use of (5), Equation (4) becomes

$$Nu = \alpha \frac{\mathrm{d}^2 \theta^*}{\mathrm{d}y^2} - c\theta^*, \tag{6}$$

where

$$c = \frac{4}{\rho c_p}\int_0^\infty K_{\lambda_0}\left(\frac{\partial e_{\lambda h}}{\partial T}\right)_0 \mathrm{d}\lambda. \tag{7}$$

Subscript "0" indicates that all quantities have been evaluated at the entrance temperature T_{w0} which is the temperature of the wall at $z = 0$.

Integrating Equation (3) we get

$$p = f(z). \tag{8}$$

On use of (8), Equation (2) becomes

$$\nu \frac{\mathrm{d}^2 u}{\mathrm{d}y^2} + g\beta\theta^* - \frac{\nu}{k'}u = -c_1, \tag{9}$$

where

$$c_1 = -\left[\frac{1}{\rho}\frac{\partial f}{\partial z} - g\beta N z\right]. \tag{10}$$

Introducing the non-dimensional variables

$$\eta = \frac{y}{L}, u_1 = \frac{uL}{\alpha c_2}, \ \theta = -\frac{\theta^*}{NLc_2}, c_2 = \frac{c_1 L^3}{\nu\alpha} \tag{11}$$

and on using (11), Equations (9) and (6) become

$$\frac{\mathrm{d}^2 u_1}{\mathrm{d}\eta^2} - Ra\theta - \frac{1}{\sigma}u_1 = -1, \tag{12}$$

$$\frac{\mathrm{d}^2\theta}{\mathrm{d}\eta^2} - F\theta = -u_1, \tag{13}$$

where $\sigma = \frac{k'}{L^2}$ is the porosity parameter, $Ra = \frac{g\beta N L^4}{\nu\alpha}$ is the Rayleigh number and $F = \frac{cL^2}{\alpha}$ is the radiation parameter.

The dimensionless velocity and the temperature boundary conditions are

$$u_1 = 0 \ \ at \ \ \eta = \pm 1,$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}\eta} \pm \frac{\theta}{\psi} = 0 \ \ at \ \ \eta = \pm 1, \tag{14}$$

where ψ is the thermal conductance ratio.

Eliminating u_1 from (12) and (13), we obtain

$$\frac{\mathrm{d}^4\theta}{\mathrm{d}\eta^4} - \left(\frac{1}{\sigma} + F\right)\frac{\mathrm{d}^2\theta}{\mathrm{d}\eta^2} + \left(Ra + \frac{F}{\sigma}\right)\theta = 1. \tag{15}$$

The solution of $\theta(\eta)$ satisfying the boundary conditions (14) is easily obtained. Achieving $\theta(\eta)$, one can determine $u_1(\eta)$ from (12) using the boundary conditions (14).

The solutions for $\theta(\eta)$ and $u_1(\eta)$ subject to the boundary conditions (14) are

$$\theta(\eta) = a_4\left[1 - a_2\cosh m_2\eta - a_3\left\{\cosh m_1\eta - a_1\cosh m_2\eta\right\}\right], \tag{16}$$

$$u_1(\eta) = a_4\Big[F - a_2\left(F - m_2^2\right)\cosh m_2\eta - a_3\left\{\left(F - m_1^2\right)\cosh m_1\eta - a_1\left(F - m_2^2\right)\cosh m_2\eta\right\}\Big] \tag{17}$$

where

$$a_1 = \frac{\psi m_1 \sinh m_1 + \cosh m_1}{\psi m_2 \sinh m_2 + \cosh m_2}$$

$$a_2 = \frac{1}{\psi m_2 \sinh m_2 + \cosh m_2},$$

$$a_3 = \frac{F - a_2\left(F - m_2^2\right)\cosh m_2}{\left(F - m_1^2\right)\cosh m_1 - a_1\left(F - m_2^2\right)\cosh m_2},$$

$$a_4 = \frac{1}{Ra + F/\sigma}, \tag{18}$$

$$m_1^2 = \frac{1}{2}\left[\left(\frac{1}{\sigma} + F\right) + \left\{\left(\frac{1}{\sigma} - F\right)^2 - 4Ra\right\}^{1/2}\right],$$

$$m_2^2 = \frac{1}{2}\left[\left(\frac{1}{\sigma} + F\right) - \left\{\left(\frac{1}{\sigma} - F\right)^2 - 4Ra\right\}^{1/2}\right] \tag{19}$$

It is observed from the Equations (16) and (17) that the velocity and temperature depend on the parameters σ, F, Ra and ψ.

Case-I: Constant wall temperature ($\psi = 0$).

The temperature distribution $\theta(\eta)$ and velocity $u_1(\eta)$ for constant wall temperature are given by

$$\theta(\eta) = \frac{1}{\left(Ra + \frac{F}{\sigma}\right)}\left[1 - \frac{m_2^2}{m_2^2 - m_1^2}\frac{\cosh m_1\eta}{\cosh m_1} + \frac{m_1^2}{m_2^2 - m_1^2}\frac{\cosh m_2\eta}{\cosh m_2}\right], \tag{20}$$

$$u_1(\eta) = \frac{1}{\left(Ra + \frac{F}{\sigma}\right)}\left[F - \frac{\left(F - m_1^2\right)m_2^2}{m_2^2 - m_1^2}\frac{\cosh m_1\eta}{\cosh m_1} + \frac{\left(F - m_2^2\right)m_1^2}{m_2^2 - m_1^2}\frac{\cosh m_2\eta}{\cosh m_2}\right], \tag{21}$$

where m_1 and m_2 are given by (19).

Case-II: Thermally insulated walls ($\psi = \infty$).

The temperature distribution $\theta(\eta)$ and velocity $u_1(\eta)$ for thermally insulated walls are given by

$$\theta(\eta) = \frac{1}{\left(Ra + \frac{F}{\sigma}\right)}\left[1 - \frac{F\left(m_2\sinh m_2\cosh m_1\eta - m_1\sinh m_1\cosh m_2\eta\right)}{m_2\left(F - m_1^2\right)\sinh m_2\cosh m_1 - m_1\left(F - m_2^2\right)\sinh m_1\cosh m_2}\right], \tag{22}$$

$$u_1(\eta)=\frac{F}{\left(Ra+\dfrac{F}{\sigma}\right)}\left[1-\frac{m_2\left(F-m_1^2\right)\sinh m_2\cosh m_1\eta-m_1\left(F-m_2^2\right)\sinh m_1\cosh m_2\eta}{m_2\left(F-m_1^2\right)\sinh m_2\cosh m_1-m_1\left(F-m_2^2\right)\sinh m_1\cosh m_2}\right],\quad(23)$$

where m_1 and m_2 are given by (19).

3. Results and Discussion

To study the effects of radiation and porosity of the porous medium on the velocity field u_1 and temperature distribution θ, we have presented the non-dimensional velocity u_1 and the temperature θ against η for various values of radiation parameter F, Rayleigh number Ra, porosity parameter σ and the thermal conductance parameter ψ in **Figures 2-9**. It is observed from **Figure 2** that the velocity $u_1(\eta)$ increases with an increase in radiation parameter F. Increasing the radiation parameter F produces significant increase in the thermal condition of the fluid. This increase in the fluid temperature induces more flow causing the velocity of the fluid there to increase. **Figure 3** shows that the velocity at any point in the flow region decreases with an increase in Rayleigh number Ra. The Rayleigh number is viewed as the ratio of buoyancy forces and the product of thermal and momentum diffusivities. Increasing value of Rayleigh number opposes the natural convection and hence the fluid velocity decreases. It is observed from **Figure 4** that the velocity u_1 increases with an increase in porosity parameter σ. Porosity is a measure of the void (or empty) spaces in a porous medium and is a fraction of the volume of voids over the total volume. Porosity influences the convection flow and so the fluid velocity increases. It is seen from **Figure 5** that the velocity decreases with an

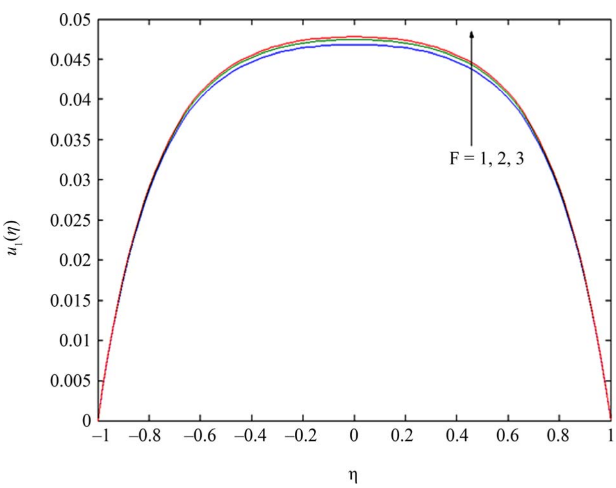

Figure 2. Variations of $u_1(\eta)$ for $Ra = 2$, $\psi = 0.5$ and $\sigma = 0.1$.

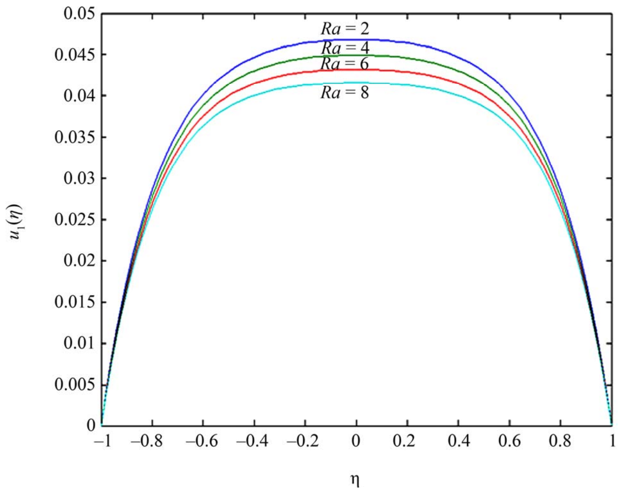

Figure 3. Variations of $u_1(\eta)$ for $F = 1$, $\psi = 0.5$ and $\sigma = 0.1$.

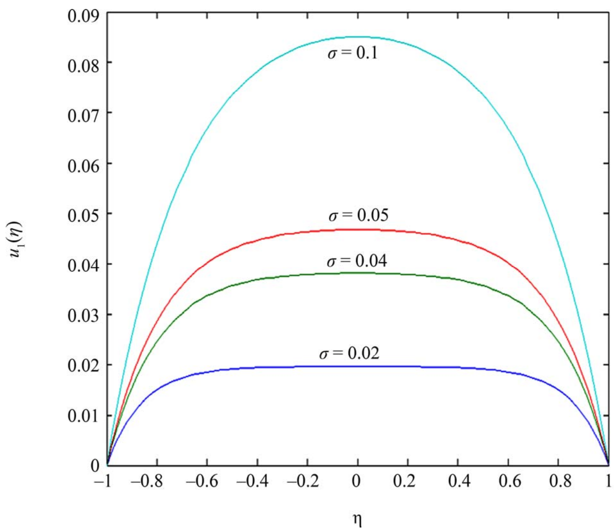

Figure 4. Variations of $u_1(\eta)$ for $F = 1$, $\psi = 0.5$ and $Ra = 1$.

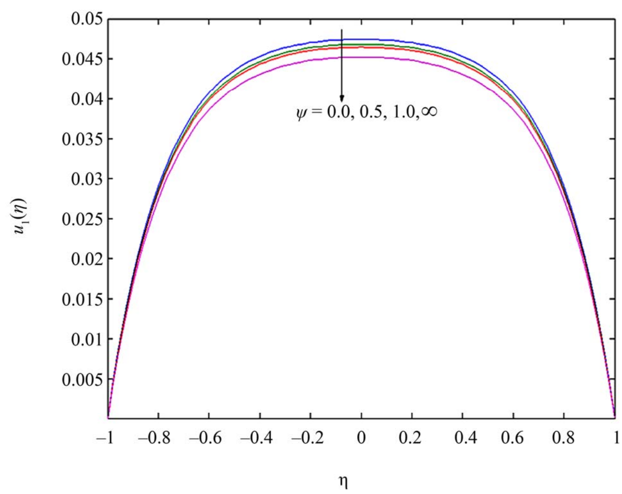

Figure 5. Variations of $u_1(\eta)$ for $F = 1$, $\sigma = 0.1$ and $Ra = 1$.

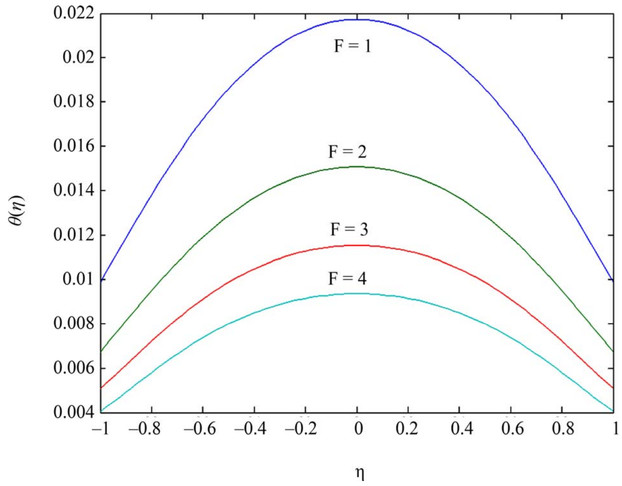

Figure 6. Variations of $\theta(\eta)$ for $\psi = 0.5$, $\sigma = 0.1$ and $Ra = 1$.

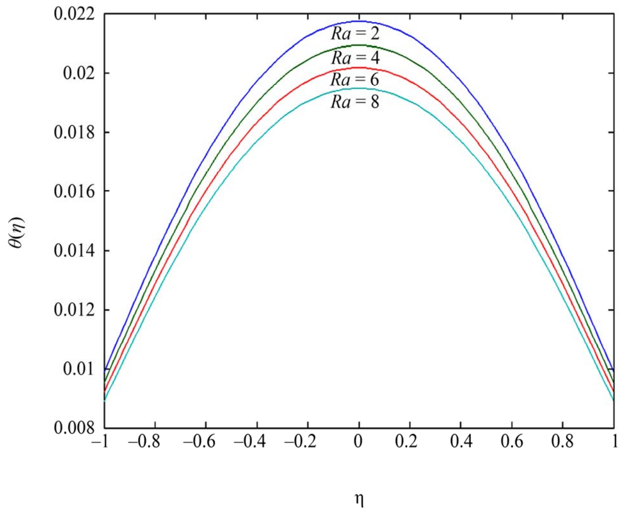

Figure 7. Variations of $\theta(\eta)$ for $F = 1$, $\sigma = 0.1$ and $\psi = 0.5$.

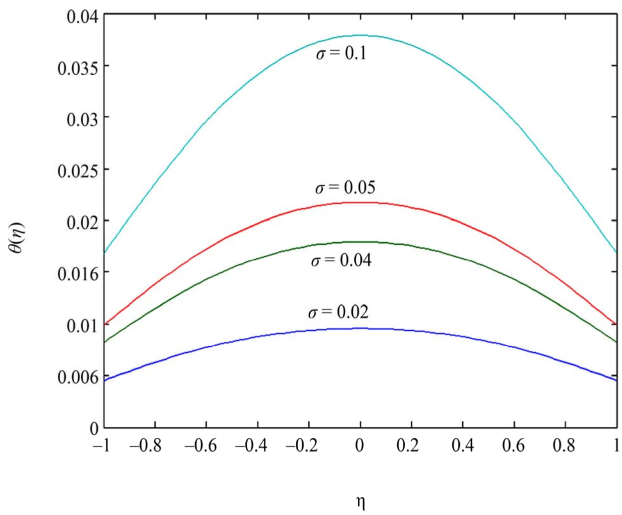

Figure 8. Variations of $\theta(\eta)$ for $F = 1$, $\psi = 0.5$ and $Ra = 1$.

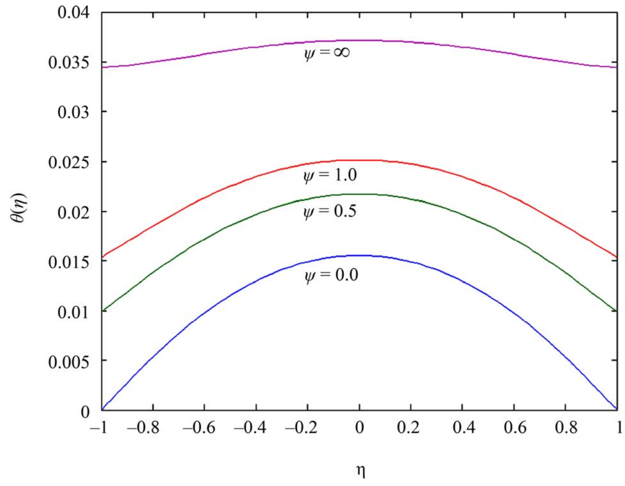

Figure 9. Variations of $\theta(\eta)$ for $F = 1$, $\sigma = 0.1$ and $Ra = 1$.

increase in thermal conductance parameter ψ. **Figures 6 and 7** reveal that the temperature θ decreases with an increase in either radiation parameter F or Rayleigh number Ra. Radiation tends to increase the rate of heat transport to the fluid. Thus the effect of radiation reduces the influence of natural convection by causing a reduction in the temperature difference between the fluid and the channel walls. The increase in radiation parameter F means the release of heat energy from the flow region and so the fluid temperature significantly decreases. It is found from **Figures 8** and **9** that the temperature θ increases with an increase in either porosity parameter σ or thermal conductance parameter ψ.

The non-dimensional shear stress at the right wall $(\eta = 1)$ of the channel is given by

$$\tau = -a_4\left[a_3\left(F - m_1^2\right)m_1\sinh m_1 + \left(a_2 - a_1a_3\right)\left(F - m_2^2\right)m_2\sinh m_2\right]. \tag{24}$$

Numerical values of non-dimensional shear stress τ at the right wall $(\eta = 1)$ of the channel are plotted against F for different values of Ra, σ and ψ in **Figures 10-12**. It is observed from **Figure 10** that for fixed values of F the magnitude of the shear stress τ at the right wall decreases with an increase in Rayleigh number Ra. **Figure 11** reveals that the magnitude of τ increases with an increase in porosity parameter σ. On the other hand, it is seen from **Figure 12** that for fixed values of F, the magnitude of τ decreases with an decrease in ψ.

The rate of heat transfer across the channel's wall is given as

$$-\left.\frac{d\theta}{d\eta}\right]_{\eta=1} = a_4\left[a_3m_1\sinh m_1 + \left(a_2 - a_1a_3\right)m_2\sinh m_2\right]. \tag{25}$$

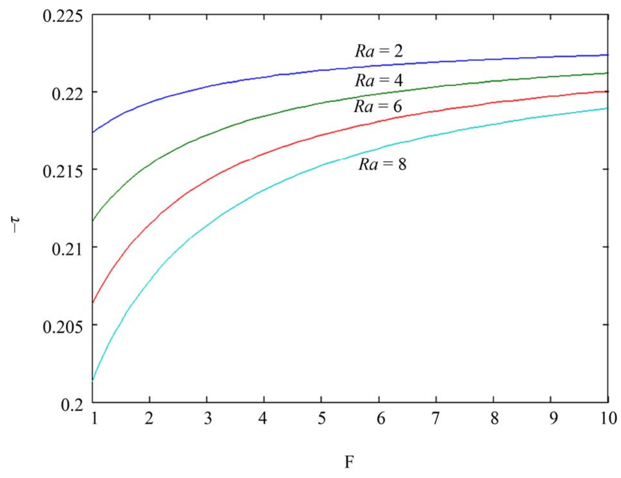

Figure 10. Variations of –*τ* against *F* for *ψ* = 0.5 and *σ* = 0.1.

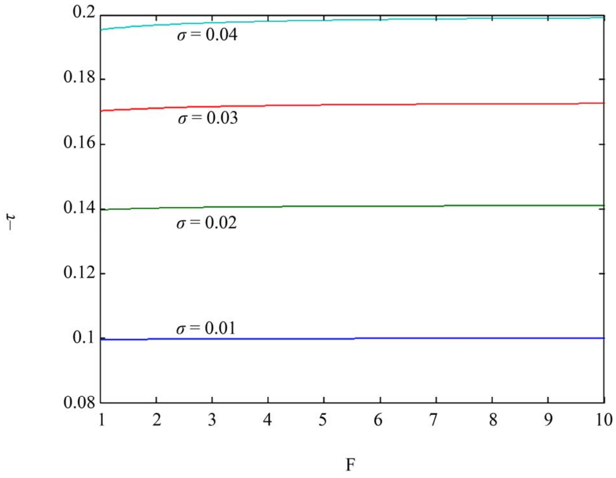

Figure 11. Variations of –*τ* against *F* for *ψ* = 0.5 and *Ra* = 2.

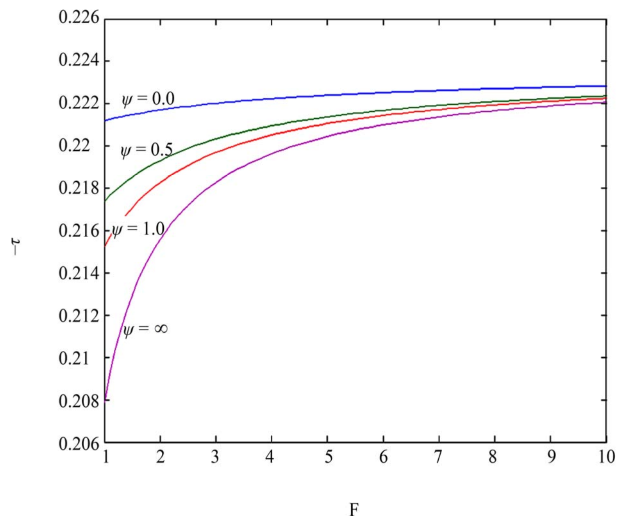

Figure 12. Variations of shear stress –*τ* against *F* for *Ra* = 2 and *σ* = 0.1.

Numerical values of the rate of heat transfer $-\theta'(1)$ are shown graphically against *F* for different values of Ra, σ and ψ in **Figures 13-15**. It is observed from **Figure 13** that for fixed values of *F*, the rate of heat transfer $-\theta'(1)$ decreases with an increase in Rayleigh number Ra. **Figure 14** reveals that the $-\theta'(1)$ increases with an increase in porosity parameter σ. On the other hand, it is seen from **Figure 15** that for fixed values of *F*, $-\theta'(1)$ decreases with an decrease in ψ.

The non-dimensional flow rate is given by

$$
\begin{aligned}
W &= \int_{-1}^{1} u_1(\eta)\,\mathrm{d}\eta \\
&= 2a_4\left[F - a_3\left(F - m_1^2\right)\frac{\sinh m_1}{m_1}\right. \\
&\quad \left. -\left(a_2 - a_1 a_3\right)\left(F - m_2^2\right)\frac{\sinh m_2}{m_2}\right].
\end{aligned} \tag{26}
$$

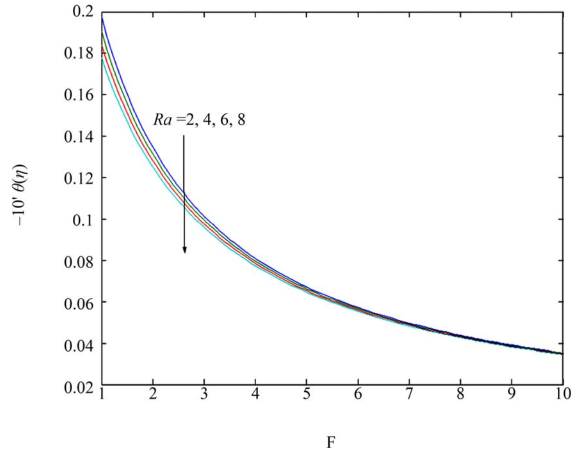

Figure 13. Variations of –*θ*'(1) against *F* for *ψ* = 0.5 and σ = 0.1.

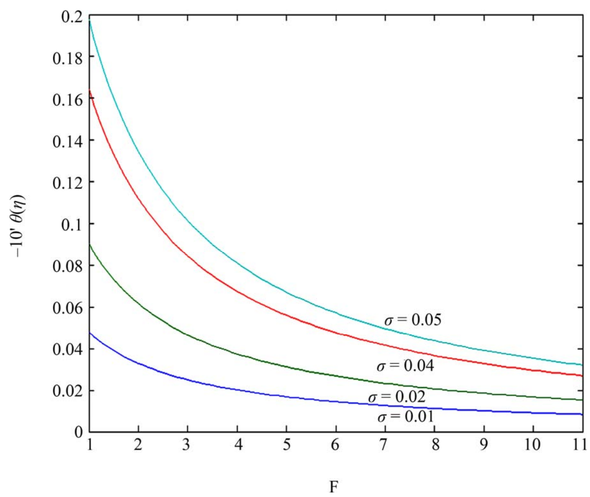

Figure 14. Variations of –*θ*'(1) against *F* for *ψ* = 0.5 and *Ra* = 2.

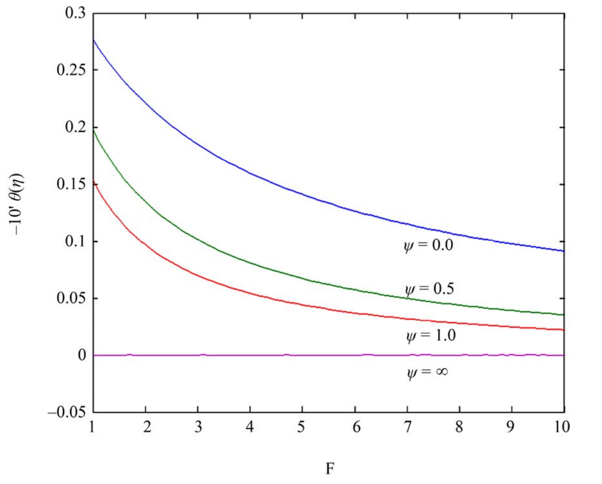

Figure 15. Variations of $-\theta'(1)$ against *F* for $\sigma = 0.1$ and *Ra* = 2.

The non-dimensional flow rate, W has been plotted against F for different values of Ra, σ and ψ in **Figures 16-18**. It is observed from **Figure 16** that for fixed values of F, the flow rate W decreases with an increase in Rayleigh number Ra. **Figure 17** reveals that flow rate W increases with an increase in porosity parameter σ. On the other hand, it is seen from **Figure 18** that for fixed values of F, W decreases with an decrease in ψ.

4. Conclusions

The fully developed free convection flow of a radiating gas between two vertical thermally conducting walls embedded in porous medium has been studied. The effects of the permeability of the porous medium and the influences of radiation parameter and thermal wall conductances on velocity and temperature fields are investigated and analyzed with the help of their graphical representa-

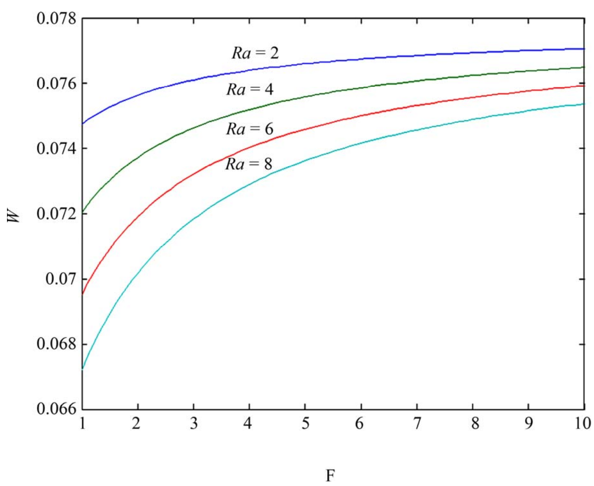

Figure 16. Variations of *W* against *F* for $\sigma = 0.1$ and $\psi = 0.5$.

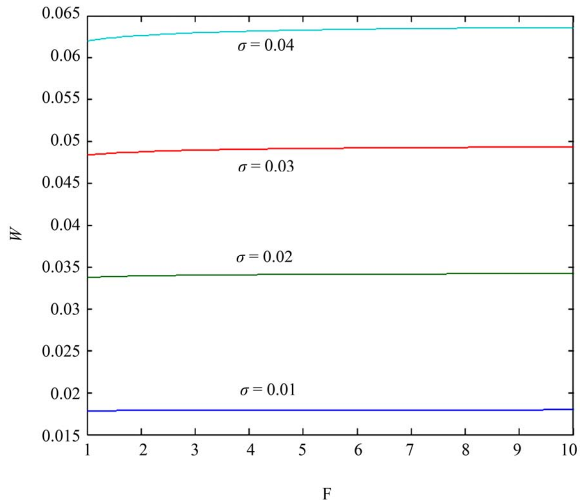

Figure 17. Variations of *W* against *F* for $\psi = 0.5$ and *Ra* = 2.

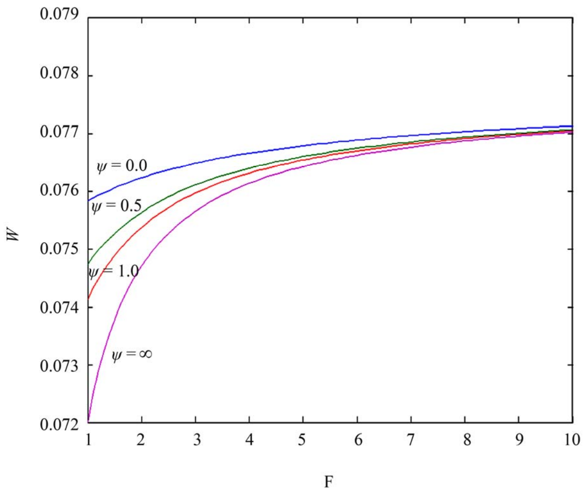

Figure 18. Variations of *W* against *F* for $\sigma = 0.1$ and *Ra* = 2.

tions. It is observed that the fluid velocity $u_1(\eta)$ increases and the temperature distribution $\theta(\eta)$ decreases with an increase in the radiation parameter F. It is also observed that both the fluid velocity and temperature in the flow field increase with an increase in the porosity parameter σ. It is found that the fluid velocity decreases while the temperature increases with an increase in the thermal conductance of the walls ψ. Further, it is found that radiation causes to decrease the rate of heat transfer to the fluid thereby reducing the effect of natural convection. The rate of flow increases with an increase in either F or Rayleigh number Ra.

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