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Effects of Radiation Absorption and Mass Transfer on the Free Convective Flow Passed a Vertical Flat Plate through a Porous Medium in an Aligned Magnetic Field

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Abstract

This article analyses the effects of radiation absorption and mass transfer on the steady free convective flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical flat plate through a porous medium with an aligned magnetic field. Analytical solutions for concentration, temperature, and velocity are obtained by solving the governing equations in two cases namely (i) when the plate is at uniform temperature and concentration and (ii) when the plate is at constant heat and mass flux. Further the rate of mass transfer in terms of the Sherwood number, rate of heat transfer in terms of Nusselt number and skin friction in terms of shear stress are also derived. The effects of various flow parameters on concentration, temperature, velocity, Sherwood number, Nusselt number and skin-friction affecting the flow field are discussed and analyzed.

Keywords: Natural convection; radiation absorption; porous medium; vertical flat plate; heat and mass transfer

MSC 2010 No.: 76R10, 80A99, 80A20

1. Introduction

Heat and mass transfer in a porous medium is prevalent in nature and many manmade technological processes. In consequence the theory of flow through porous media has emerged as a vibrant discipline of intensive research activity. Recent developments in modern technology have intensified interest of many researchers in the study of simultaneous heat and mass transfer from different geometries through a porous medium in fluids. Involved in this study is a wide range of applications in engineering, geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed bed catalytic reactors, cooling of nuclear reactors, underground energy transport, etc. Free convective flows are of great interest in a number of industrial applications such as geothermal systems, fiber and granular insulation, etc.

A study of the effect of a magnetic field on free convective flows in liquid-metals, electrolytes and ionized gases is important. The impact of the magnetic field on viscous, incompressible, electrically conducting fluid is also of importance in applications such as purification of crude oil, extrusion of plastics in the manufacture of Rayon and Nylon, etc. The presence of an electrically conducting fluid under the magnetic field has the advantage that the rate of cooling of threads and sheets of polymer materials will be controlled effectively. The available hydrodynamic solutions include the effects of the magnetic field, which is possible as most of the industrial fluids are electrically conducting. For example, liquid metal MHD takes its root in the hydrodynamics of incompressible media which is increasingly gaining importance in the metallurgical industry, nuclear reactor, sodium cooling system, storage and electrical power generation.

Hydromagnetic flow is important due to its industrial applications. For instance, it is used to deal with the problem of the cooling of nuclear reactors by fluids having very low Prandtl number (Liquid metals have small Prandtl number of order 0.001~0.1 e.g. $Pr = 0.01$ for Bismuth, $Pr = 0.023$ for Mercury etc.). It is used as a coolant because of very high thermal conductivity. It can transport heat even if small temperature difference exists between the surface and the fluid. For this reason, liquid metals are used as coolants in nuclear reactors for disposal of waste heat. Further, the velocity field and temperature distribution of the liquid metals are modified in the presence of transverse magnetic field because of their high electrical conductivity which is a function of temperature and in the case of metals, varies inversely with respect to the temperature.

In industries, many transport processes exist in which heat and mass transfer take place simultaneously as a result of combined buoyancy effect in the presence of thermal radiation. Hence, radioactive heat and mass transfer play an important role in the manufacturing industries for the design of fins, steel rolling, nuclear power plants, gas turbines, various propulsion devices for aircraft, missiles, satellites, materials processing, energy utilization, temperature measurements, remote sensing for astronomy, space exploration, food processing, cryogenic engineering, combustion and furnace design as well as numerous agricultural, health and military applications.

Free convective flow past a vertical plate has been studied extensively by Ostrich (1953). Free convective heat transfer due to the simultaneous action of buoyancy and induced magnetic forces was investigated by Sparrow and Cess (1961). They observed that the free convective heat transfer to liquid metals might be significantly affected by the presence of a magnetic field. Gribben (1965) considered the MHD boundary layer flow over a semi-infinite plate with an aligned magnetic field in the presence of a pressure gradient. He obtained solutions for large and small magnetic Prandtl numbers using the method of matched asymptotic expansion.

Cess (1996) investigated the interaction of radiation with laminar free convection heat transfer from a vertical plate for absorbing and emitting fluid in the optically thick region using the singular perturbation technique. Bankston et al. (1977) studied the interaction of thermal radiation and free convection on a steady flow. The steady state solution using similarity variable has been determined by Gebhart and Pera (1971) for natural convection on a vertical plate with variable temperature and variable mass diffusion. Soundalgekar (1979) presented an exact solution to the flow of a viscous fluid past an impulsively started infinite isothermal vertical plate with mass transfer. Free convection effects on the flow past a vertical flat plate were studied by Vedhanayagam et al. (1980). Raptis and Kafousias (1982) studied the influence of a magnetic field upon the steady free convective flow through a porous medium bounded by an infinite vertical plate with constant suction velocity and when the plate temperature is also constant.

Bejan and Khair (1985) examined heat and mass transfer by natural convection near a vertical surface in a porous medium by scale analysis and similarity transformation. Sahoo et al. (1986) discussed the MHD free convective flow past a vertical plate through a porous medium in the presence of foreign mass. Kim et al. (1989) solved the problem of natural convective flow through a porous medium past a plate. Mass diffusion and natural convection flow past a flat plate were studied by Chandrasekhara et al. (1992). Shanker and Kishan (1997) discussed the effects of mass transfer on the MHD flow past an impulsively started vertical plate with variable temperature or constant heat flux. Raptis (1998) analyzed both the thermal radiation and free convective flow through a porous medium by using a perturbation technique. Chamkha and Khaled (2000) investigated the hydromagnetic combined heat and mass transfer by natural convection from a permeable surface embedded in a fluid saturated porous medium. Chamkha et al. (2001) studied the radiation effects on free convective flow past a semi-infinite vertical plate with mass transfer. Muthucumaraswamy and Ganesan (2003) studied the effects of radiation on the flow past an impulsively started infinite vertical plate with variable temperatures using Laplace transform technique.

The effects of chemical reaction and radiation absorption on free convective flow through a porous medium with a variable suction in the presence of uniform magnetic field were studied by Sudheer Babu and Satyanarayana (2009). Ahmed and Alam Sarker (2009) presented the problem of a steady two - dimensional natural convective flow of a viscous incompressible and electrically conducting fluid past a vertical impermeable flat plate in the presence of a uniform transverse magnetic field. Saravana et al. (2011) studied the effects of mass transfer on the MHD viscous flow past an impulsively started infinite vertical plate with constant mass flux. Manjulatha et al. (2012) discussed the effect of an aligned magnetic field on two-dimensional MHD free convective flow of a viscous incompressible fluid through a porous medium confined in a vertical flat plate with temperature dependent heat absorption or generation in two cases of boundary conditions. The effects of radiation and aligned magnetic field on an unsteady MHD oscillatory flow in a channel filled with a saturated porous medium were investigated by Manjulatha et al. (2013).

The combined effects of radiation absorption and mass transfer with an aligned magnetic field have not been studied so far. Hence the aim of the present investigation is to formulate and analyze the effect of radiation absorption and mass transfer on two–dimensional MHD free convective flow of a viscous incompressible fluid through a porous medium confined to a vertical flat plate with an aligned magnetic field.

2. Mathematical Formulation

Here the x'-axis is in the vertically upward direction along the plate and y'-axis normal to it as shown in Figure 1.

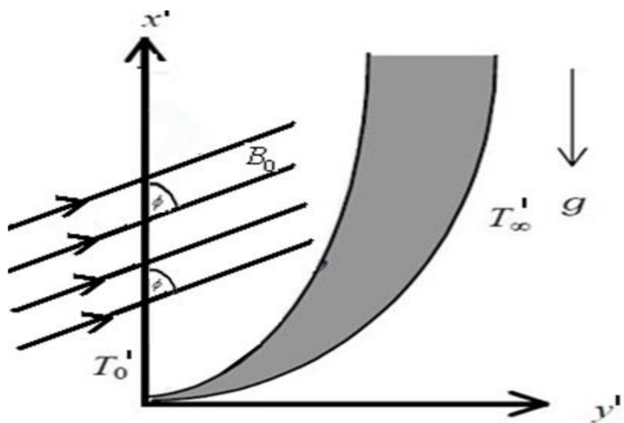


Figure1. The flow configuration and co-ordinate system

It is assumed that

i. the induced magnetic field is negligible as the magnetic Reynolds number of the flow is assumed to be very small.
ii. the viscous and Joule's dissipation terms are negligible in the energy equation.
iii. there is no applied voltage which implies the absence of an electric field.
iv. all the physical variables are dependent on y' only since the plate is considered infinite in x' direction.

Under the above assumptions, the governing equations of the problem are given by

Equation of Continuity

$$\frac{\partial v'}{\partial y'} = 0 \, , \tag{1}$$

Equation of Momentum

$$v' \frac{\partial u'}{\partial y'} = \upsilon \frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) - \frac{\sigma B_0^2 \sin^2\phi}{\rho_\infty} u' - \frac{\mu}{\rho_\infty k'} u' \,, \tag{2}$$

Equation of Energy

$$v' \frac{\partial T'}{\partial y'} = \frac{K}{\rho_\infty c_p} \frac{\partial^2 T'}{\partial y'^2} + \frac{Q_0 (T' - T'_\infty)}{\rho_\infty c_p} + Q'_1 (C' - C'_\infty) \,, \tag{3}$$

Equation of Species Diffusion

$$v' \frac{\partial C'}{\partial y'} = D \frac{\partial^2 C'}{\partial y'^2} \,, \tag{4}$$

with the initial and appropriate boundary conditions:

Case (i): Uniform concentration and temperature

$$\begin{aligned} &u' = 0,\ T' = T'_0, C' = C'_0 \quad at \quad y' = 0, \\ &u' \to 0,\ T' \to T'_\infty, C' \to C'_\infty \ \ at \ \ y' \to \infty \,. \end{aligned} \tag{5a}$$

Case (ii): Constant heat and mass flux

$$\begin{aligned} &u' = 0, \quad \frac{\partial T'}{\partial y'} = \frac{-q}{K}, \ \ \frac{\partial C'}{\partial y'} = \frac{-m}{D} \quad at \quad y' = 0, \\ &u' \to 0, \quad T' \to T'_\infty, \quad C' \to C'_\infty \quad as \quad y' \to \infty \,. \end{aligned} \tag{5b}$$

Here, T' is the temperature of the fluid in the boundary layer, g is the acceleration due to gravity, B_0 is the uniform aligned magnetic field strength, β is the volumetric coefficient of expansion for heat transfer, β^* is the volumetric coefficient of expansion for mass transfer, K is the thermal conductivity, v'_0 is the constant suction velocity, ρ_∞ is the density of the fluid, c_p is the specific heat at constant pressure, T'_∞ is the temperature of the ambient fluid, υ is the kinematic viscosity of the fluid and D is the mass diffusivity. From the equation of continuity (1) we consider the velocity as $v' = -v'_0$.

Introducing the following non dimensional quantities into the equations (2) - (5),

$$y = \frac{v'_0 y'}{\vartheta}, u = \frac{u'}{v'_0}, \theta = \frac{T' - T'_\infty}{T'_0 - T'_\infty}, C = \frac{C' - C'_\infty}{C'_0 - C'_\infty} \,, k = \frac{k' v'^2_0}{\vartheta^2},$$

$$Sc = \frac{\vartheta}{D} \; , Pr = \frac{\mu c_p}{K}, M = \frac{\sigma B_0^2 \vartheta}{\rho_\infty \upsilon_0^2} \; , Q = \frac{Q_0 \vartheta}{\rho_\infty c_p \upsilon_0'^2},$$

$$Gr = \frac{g\beta(T_0' - T_\infty')\vartheta}{\upsilon_0'^3} \; , Gm = \frac{g\beta^*(C_0' - C_\infty')\vartheta}{\upsilon_0'^3}, Q_1 = \frac{Q_1'(C_0' - C_\infty')\vartheta}{\upsilon_0'^2 (T_0' - T_\infty')} . \tag{6}$$

we get

$$\frac{d^2u}{dy^2} + \frac{du}{dy} - \left(M \, Sin^2\emptyset + \frac{1}{k}\right) u + Gr\,\theta + Gm\,C = 0 \; , \tag{7}$$

$$\frac{d^2\theta}{dy^2} + Pr\frac{d\theta}{dy} + Pr\,Q\theta + PrQ_1C = 0 \, , \tag{8}$$

$$\frac{d^2C}{dy^2} + Sc\frac{dC}{dy} = 0 \, , \tag{9}$$

with the corresponding boundary conditions:

Case (i): Uniform Concentration and Temperature

$$u = 0, \quad \theta = 1, \quad C = 1 \quad at \quad y = o, \tag{10a}$$

$$u \to 0, \theta \to 0, \; C \to 0 \quad as \quad y \to \infty.$$

Case (ii): Constant Heat and Mass Flux

$$\begin{aligned} &u = 0, \quad \frac{d\theta}{dy} = -1, \; \frac{dC}{dy} = -1, \quad at \quad y = 0, \\ &u \to 0, \; \theta \to 0, \; C \to 0 \quad as \quad y \to \infty \, . \end{aligned} \tag{10b}$$

Here, Gr is the Grashof number for heat transfer, Gm is the Grashof number for mass transfer, Q is the heat source parameter, Q_1 is the radiation absorption coefficient, Pr is the Prandtl number, Sc is the Schmidt number, M is the magnetic field parameter, k is the permeability parameter and ϕ is an align angle.

3. Method of Solution

The equations (7), (8) and (9) are solved subject to the boundary conditions (10). The following solutions are obtained for the concentration, temperature and velocity of the flow field in two different cases:

Case (i): Uniform Concentration and Temperature

$$C = e^{-m_1 y}, \tag{11}$$

$$\theta = A_2\, e^{-m_2 y} - A_1\, \mathrm{e}^{-m_1 y}, \tag{12}$$

$$u = A_6\, \mathrm{e}^{-m_1 y} + A_3\, e^{-m_2 y} + A_7\, e^{-m_3 y}. \tag{13}$$

Skin Friction

The skin-friction coefficient (τ) at the plate is given by

$$\tau = \left[\frac{\partial u}{\partial y}\right]_{y=0}. \tag{14}$$

Using equations (13) and (14), we obtain the skin friction as

$$\tau = -m_1 A_6 - m_2 A_3 - m_3 A_7 . \tag{15}$$

Nusselt Number

The rate of heat transfer coefficient (*Nu)* at the plate is given by

$$Nu = \left[\frac{\partial \theta}{\partial y}\right]_{y=0}. \tag{16}$$

Using equations (12) and (16), we obtain the Nusselt number as

$$Nu = m_1 A_1 - m_2 A_2 . \tag{17}$$

Sherwood Number

The rate of mass transfer coefficient (*Sh*) at the plate is given by

$$Sh = \left[\frac{\partial c}{\partial y}\right]_{y\ =0}. \tag{18}$$

Using equations (11) and (18), we obtain the Sherwood number as

$$Sh = -m_1. \tag{19}$$

Case (ii): Constant Heat and Mass Flux

$$C = \frac{1}{m_1} e^{-m_1 y}, \tag{20}$$

$$\theta = A_8 e^{-m_1 y} + A_9 e^{-m_2 y}, \tag{21}$$

$$u = A_{14} e^{-m_1 y} + A_{11} e^{-m_2 y} + A_{13} e^{-m_3 y}. \tag{22}$$

Skin Friction

Using equations (14) and (22), we obtain the skin friction as

$$\tau = -m_1 A_{14} - m_2 A_{11} - m_3 A_{13}. \tag{23}$$

Nusselt Number

Using equations (16) and (21), we obtain the Nusselt number as

$$Nu = -m_1 A_8 - m_2 A_9. \tag{24}$$

Sherwood number

Using equations (18) and (20), we obtain the Sherwood number as

$$Sh = -1. \tag{25}$$

Here,

$$M_1 = M\, Sin^2\emptyset,\ m_1 = Sc,\ m_2 = \frac{Pr + \sqrt{Pr^2 - 4\,Pr\,Q}}{2},\ m_3 = \frac{1 + \sqrt{1 + 4M_1}}{2},$$

$$A_1 = \frac{Pr\ Q_1}{m_1^2 - Prm_1 + PrQ_1},\ A_2 = 1 + A_1,\ A_3 = \frac{-Gr\ A_2}{(m_2^2 - m_2 - M_1)},\ A_4 = \frac{GrA_1}{(m_1^2 - m_1 - M_1)},$$

$$A_5 = \frac{Gm}{(m_1^2 - m_1 - M_1)},\ A_6 = A_4 - A_5,\ A_7 = -(A_3 + A_6),$$

$$A_8 = \frac{-PrQ_1}{m_1(m_1^2 - Prm_1 + Pr\,Q)},\ A_9 = \frac{1 - m_1 A_8}{m_2},\ A_{10} = \frac{-GrA_8}{(m_1^2 - m_1 - M_1)},$$

$$A_{11} = \frac{-GrA_9}{(m_2^2 - m_2 - M_1)},\ A_{12} = \frac{-Gm}{m_1(m_1^2 - m_1 - M_1)},\ A_{13} = -(A_{10} + A_{11} + A_{12}),$$

$$A_{14} = A_{10} + A_{12}.$$

4. Results and Discussion

In order to get a physical insight into the problem, some numerical computations are carried out for the non-dimensional concentration *C*, temperature θ, velocity *u*, Sherwood number *Sh*, Nusselt number *Nu* and skin-friction τ in terms of the parameters *Gr, Gm, Sc, Pr, M,Q* , Q_1 ,*k* and align angle ϕ in two cases, namely, uniform concentration and temperature from figures 2 to 9,and constant heat and mass flux from figures 10 to 18with tables 1to3.The values are chosen only for the liquid metals with low Prandtl numbers such as *Pr* = 0.004 (Sodium), *Pr* = 0.05 (Lithium), *Pr* = 0.72 (Air) and *Pr* = 0.94 (Ammonia) at $649^0 c$ and the values of Schmidt number are chosen to represent the presence of species by water vapor(0.60), Oxygen (0.66), Ammonia (0.78) and Carbon dioxide (0.94) at $25^0 c$ temperature with one atmospheric pressure.

The values of *Gr* = 5, *Gm* = 5, *Sc* = 0.66, *Pr* = 0.72, *Q* = 0.05, Q_1 = 0.01, *M* = 5, *k* = 0.5 and ϕ = π/6 are chosen to present the graphs for the velocity in both the cases.

Case (i): Uniform Concentration and Temperature

Figure 2 concerns the effect of the Schmidt number on the concentration field. It is noted that the concentration at all points in the flow field decreases as the Schmidt number increases.

Figure 3 shows the influence of Prandtl number on the temperature distribution. It is observed that the temperature is greater for Sodium than for Lithium or Air or Ammonia. It is because the thermal conductivity of the fluid decreases with increasing *Pr* and hence, the thermal boundary layer thickness decreases with increasing *Pr*.

Figures 4 to 9 show the effects of Grashof number for heat and mass transfer, magnetic field parameter, radiation absorption coefficient, permeability parameter and angle ϕ on the velocity field when the plate is cooled by free convective currents (i.e., *Gr* > 0, *Gm* > 0). Figure 4 shows the velocity profile for different values of thermal Grashof number on the velocity field. It is observed that the velocity increases with an increase of Grashof number for heat transfer. It is noticed that the velocity increases more rapidly near the plate and after it reaches a maximum value at *Y*=1, and the velocity decreases as we move away from the plate. The effect of Grashof number for mass transfer on the velocity field is shown in Figure 5. It is found that the velocity increases with an increase of Grashof number for mass transfer. Figure 6 describes the behavior of the velocity field with a variation in the magnetic field parameter. It is seen that the velocity decreases as the magnetic field parameter increases. Figure 7 depicts the variation in the velocity for different values of radiation absorption coefficient. It is found that the velocity increases with an increase of the radiation absorption coefficient. Figure 8indicatesthat the velocity accelerates as the permeability parameter increases. Aligned angle ϕ has reduced effects on the dimensionless velocity as shown in Figure 9. From numerical calculations, an exactly reverse trend is noticed in all these cases when the plate is heated by free convection currents (i.e., $Gr < 0$, $Gm < 0$). Figures are not produced to avoid space consumption.

The numerical values of Sherwood number are tabulated in Table 1. It is found that the Sherwood number decreases with an increase in Schmidt number. Table 2 represents the numerical values of the rate of heat transfer in terms of Nusselt number due to variation in Schmidt number, Prandtl number, heat source parameter and radiation absorption coefficient. It is observed, from this table, Nusselt number, but the trend is just reversed with increasing heat source parameter or radiation absorption coefficient.

Table 3 shows the numerical values of skin friction for different values of material parameters for cooling of the plate. It is observed that an increase in the thermal Grashof number or modified Grashof number or heat source parameter or radiation absorption coefficient or permeability parameter leads to a rise in the skin friction. An increase in the Schmidt number or Prandtl number or magnetic field parameter or angle ϕ leads to fall in the skin friction in the case of cooling of the plate. From numerical computations, it is found that an exactly opposite trend exhibits in the case of heating of the plate.

Case (ii): Constant Heat and Mass Flux

The concentration profiles for different values of the Schmidt number are plotted in Figure 10. It is seen from this figure that the concentration level decreases as the Schmidt number increases. The effect of Prandtl number on the temperature profile has already been illustrated in Figure 11. It is observed that as the Prandtl number increases, the temperature decreases in general for Pr = 0.004, 0.05, 0.72, and it is high for Pr = 0.94. The influence of the heat source parameter on the temperature of the fluid has been shown in Figure 12. It is noticed that the temperature decreases as the heat source parameter increases. From the numerical computations a similar trend is observed with increasing radiation absorption coefficient.

Figures 13 to 18 illustrate the distribution of dimensionless velocity for various parameters such as Gr, Gm, M, Q_1, k and angle ϕ when the plate is cooled by free convection currents (i.e., $Gr > 0$, $Gm > 0$). The effect of thermal Grashof number on the velocity distribution is presented in Figure 13. It is found that the velocity of the fluid in the medium increases due to an increase of thermal Grashof number. Similarly, the velocity distribution for mass Grashof number has been presented in Figure 14. From this figure, it is evident that the velocity increases as the mass Grashof number is enhanced. Figure 15 demonstrates the velocity profile against a span wise distance in the boundary layer for different values of the magnetic field parameter. As expected, the velocity decreases due to an increase in the magnetic field parameter. Figure 16 displays the variation in the velocity distribution for various values of radiation absorption coefficient. The figure reveals that the velocity increases with the increasing values of radiation absorption coefficient. The effect of permeability parameter on the velocity regime has been depicted in Figure 17. It is observed that an increase in the permeability parameter leads to a rise in the velocity. Figure 18 presents typical profiles for velocity for various values of the aligned angle ϕ. It is seen that an increase in the value of ϕ clearly reduces the fluid velocity. From numerical calculations, an exactly reverse trend is noticed in all these cases when the plate is heated by free convection currents (i.e., $Gr < 0$, $Gm < 0$). Figures are not produced to avoid space consumption.

Knowing the concentration, temperature and velocity it is customary to study the rate of mass transfer, skin friction and the rate of heat transfer with the help of tables 1 to 3. It is clear from Table1 that the Sherwood number attains a constant value, which is equal to -1 in the case of constant heat and mass flux. From Table 2, the Nusselt number was found to increase with increasing values of Schmidt number for 0.60, 0.78, 0.94, and it is low for $Sc = 0.66$ of the fluid. It was also observed that the Nusselt number increases with increasing Prandtl number for 0.004, 0.05, but it is low for $Pr = 0.94$. Similarly, the rate of heat transfer increases for an increase of $Q = 0.00, 0.05, 0.10$ as is observed from Table 2. Further, the Nusselt number decreases with an increase in radiation absorption coefficient.

Table 3 represents the numerical values of skin-friction for cooling ($Gr > 0$, $Gm > 0$). It is observed that an increase in Gr or Gm or Q or Q_1 or k leads to an increase in shear stress while an increase in Sc or M or ϕ leads to a decrease in shear stress and the shear stress increases for an increase of $Pr = 0.004, 0.05$, and it is low for $Pr = 0.94$. From numerical calculations, the shear stress is observed to increase with an increase of Sc or M or ϕ while it decreases as Gr or Gm or Q or Q_1 or k increases in the case of heating of the plate. Also, it is observed that the shear stress decreases for an increase of the Prandtl number $Pr = 0.004, 0.05$, and it is high for $Pr = 0.94$.

When the magnetic field is normal to the flow direction and in the absence of radiation absorption, heat source and porous media; the results are found to be in good agreement with the results of Ahmed and Alam Sarkar (2009).

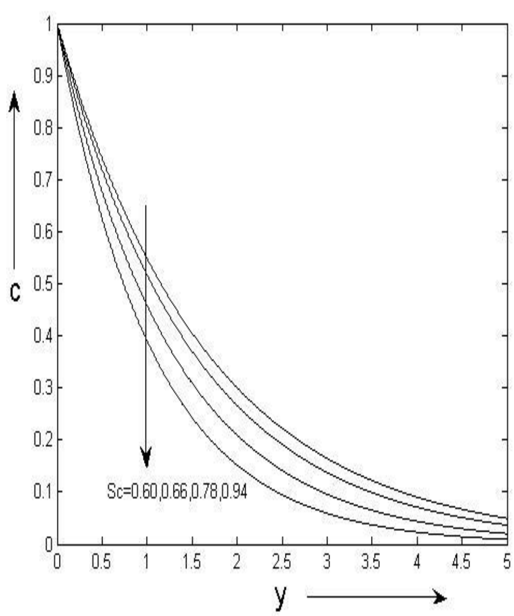


Figure2. Effect of *Sc* on concentration field

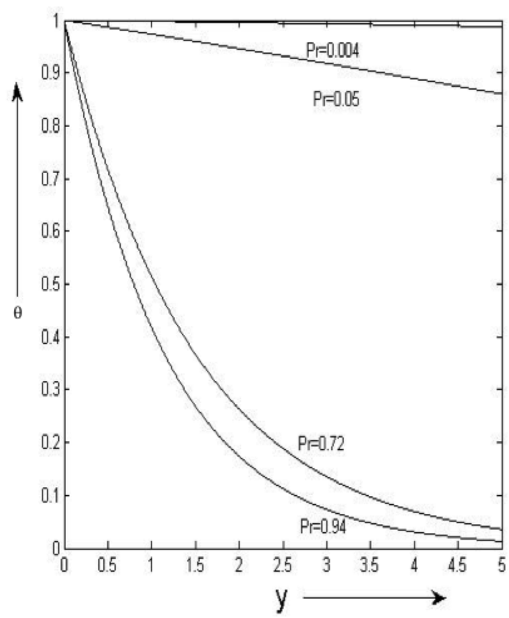


Figure 3. Effect of *Pr* on temperature field

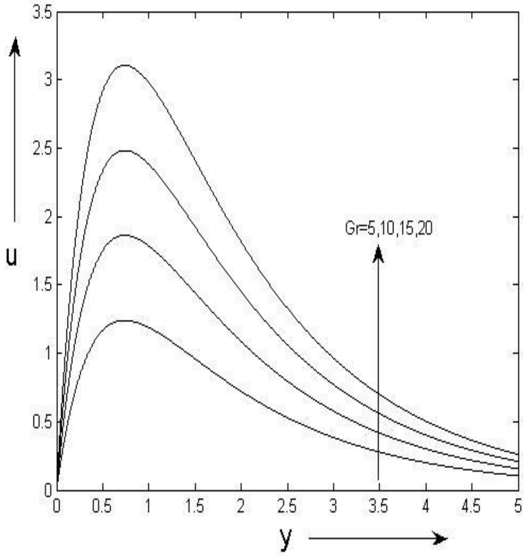


Figure 4. Effect of *Gr* on velocity field

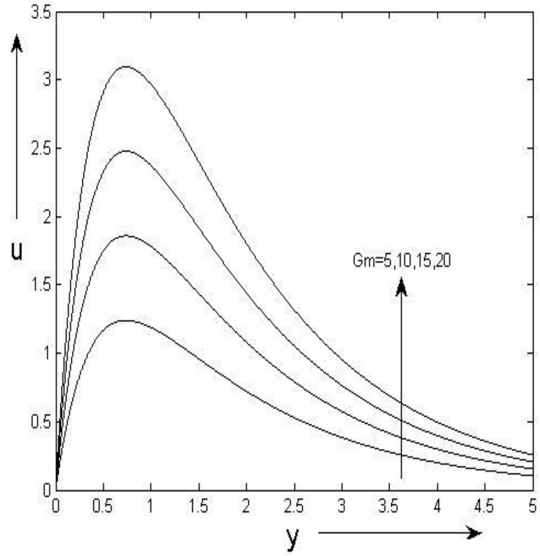


Figure5. Effect of *Gm* on velocity field

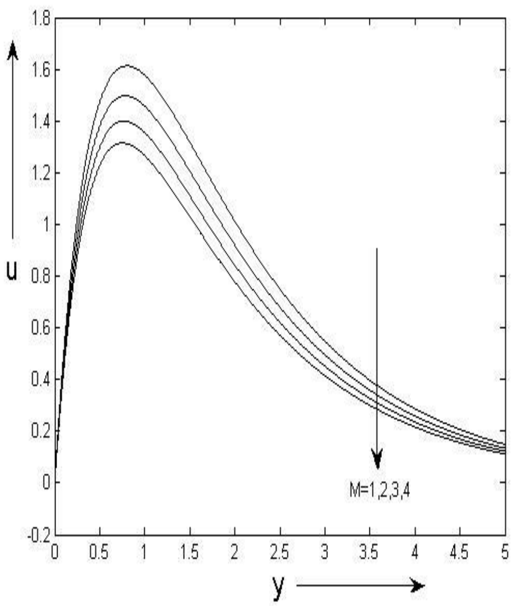


Figure 6. Effect of *M* on velocity field

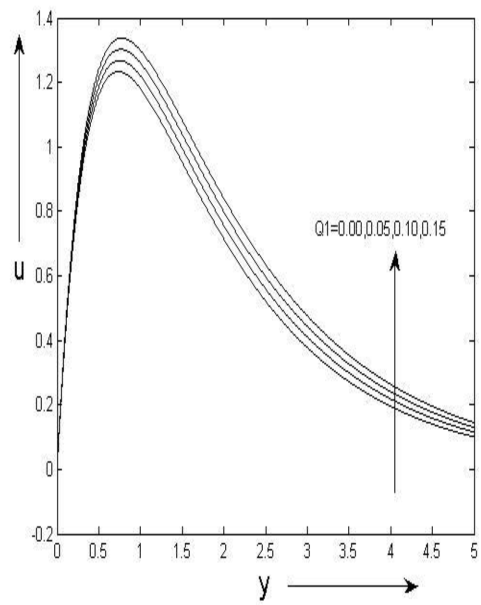


Figure 7. Effect of Q_1 on velocity field

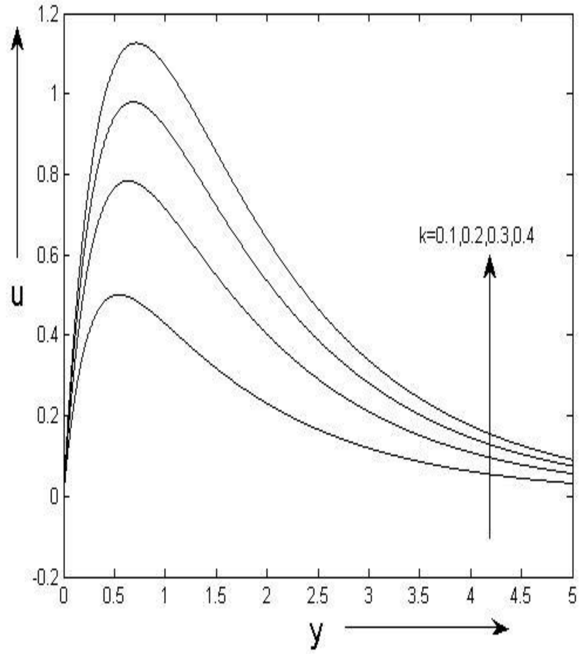


Figure 8. Effect of k on velocity field

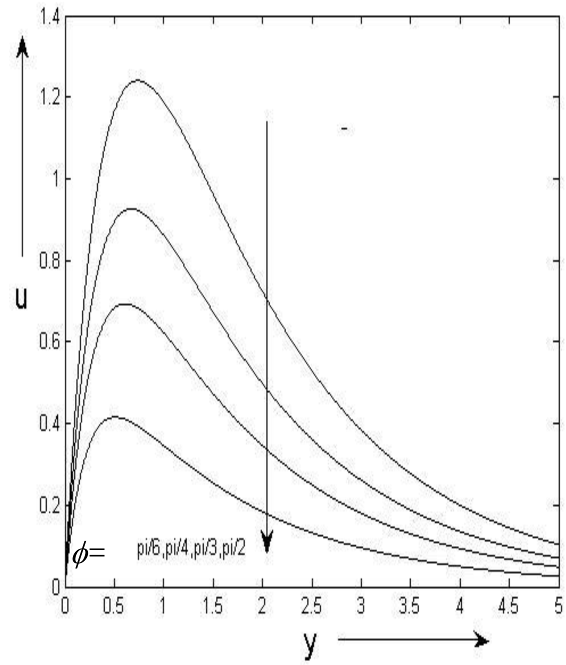
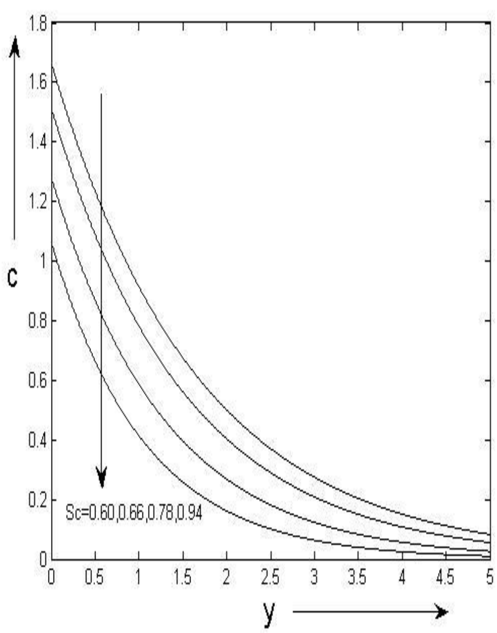


Figure 9. Effect of ϕ on velocity field



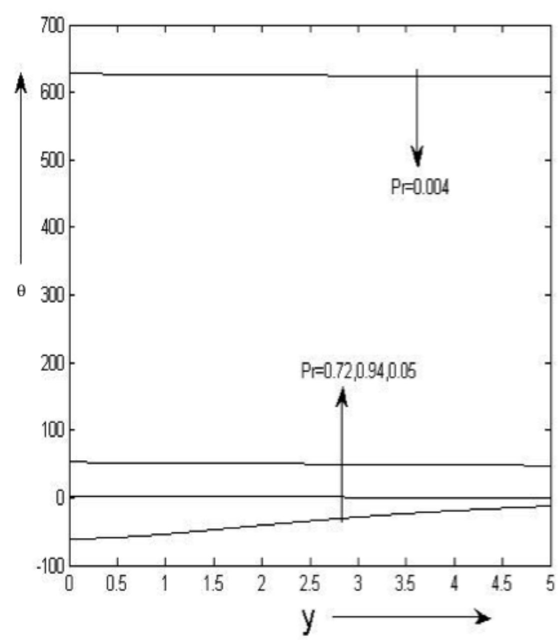
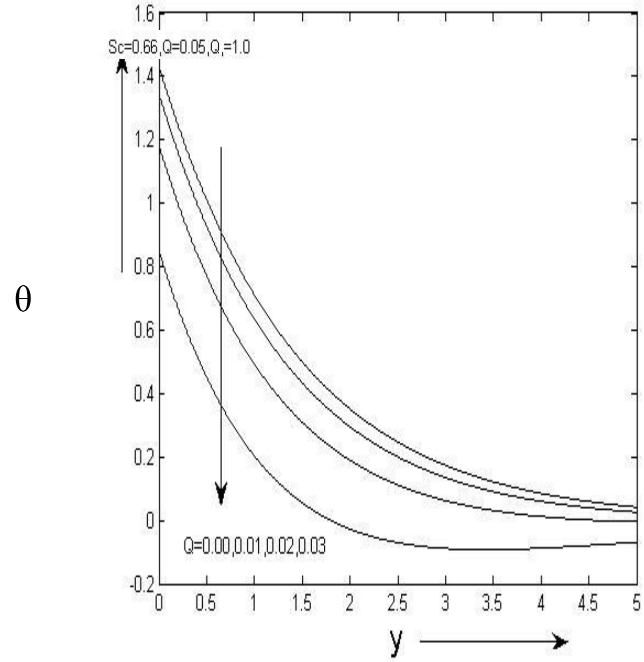


Figure10. Effect of *Sc* on concentration field

Figure11. Effect of *Pr* on temperature field



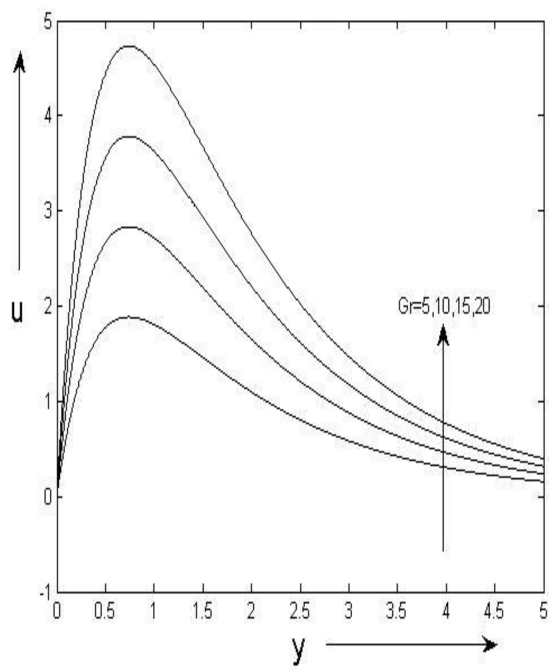


Figure 12. Effect of *Q* on temperature field

Figure 13. Effect of *Gr* on velocity field

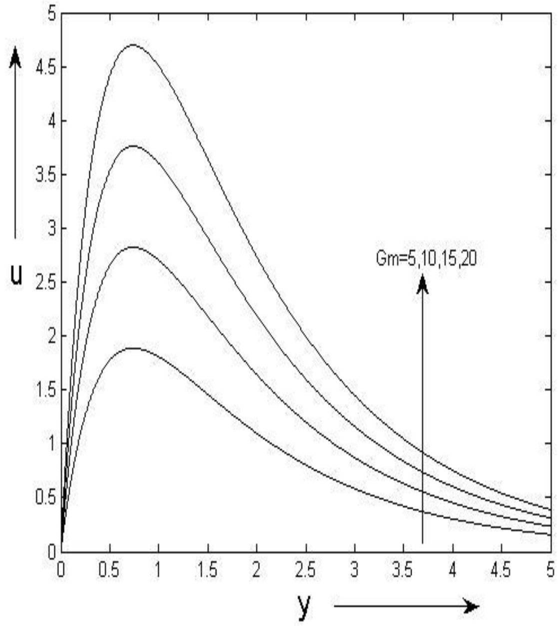


Figure 14. Effect of *Gm* on velocity field

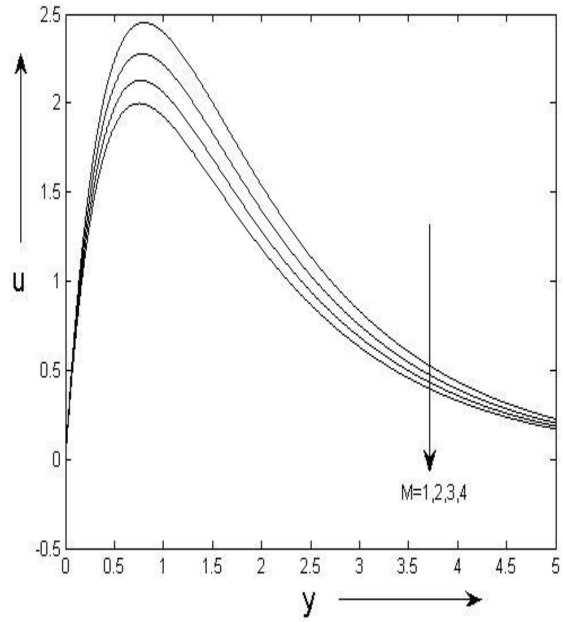


Figure 15. Effect of *M* on velocity field

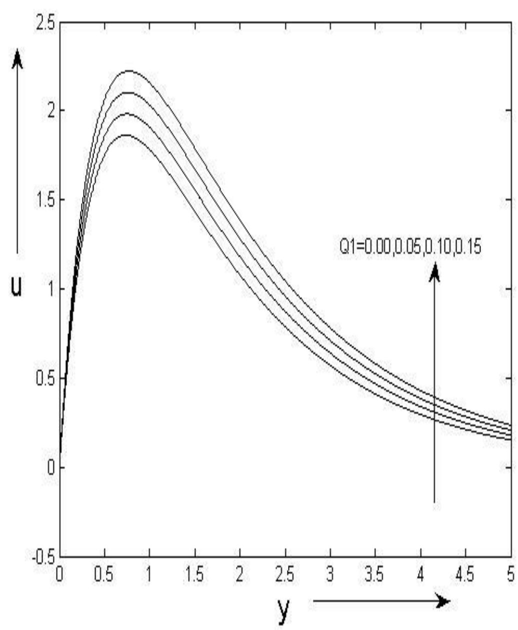


Figure 16. Effect of Q_1 on velocity field

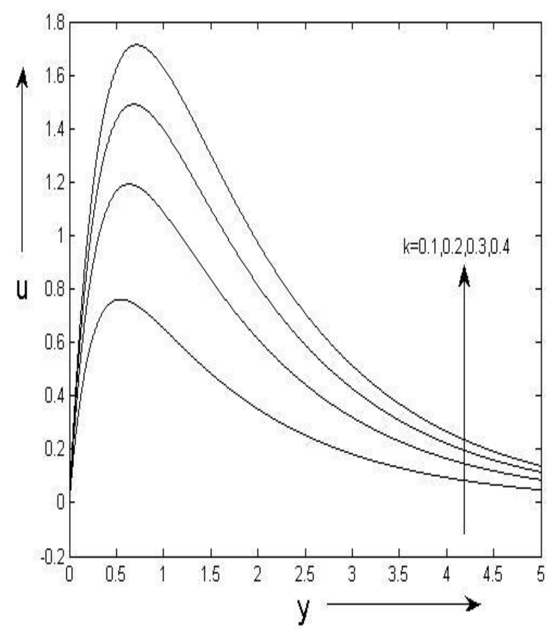


Figure 17. Effect of *k* on velocity field

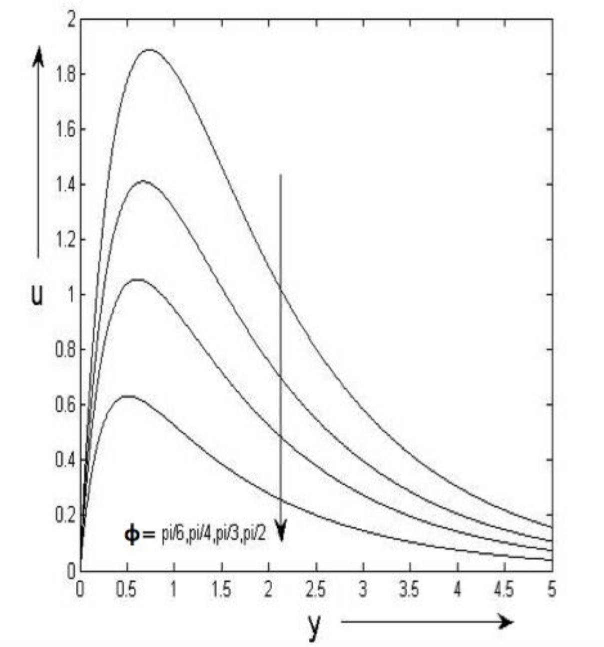


Figure18. Effect of ϕ on velocity field

Table 1. The rate of mass transfer (Sherwood number)

Sc	**Case (i)**	**Case (ii)**
0.60	-0.6000	-1.0000
0.66	-0.6600	-1.0000
0.78	-0.7800	-1.0000
0.94	-0.9400	-1.0000

Table 2. The rate of heat transfer (Nusselt number)

Sc	***Pr***	***Q***	Q_1	**Case (i)**	**Case (ii)**
0.60	0.72	0.05	0.01	-0.6636	0.5208
0.66	0.72	0.05	0.01	-0.6657	-2.9911
0.78	0.72	0.05	0.01	-0.6720	1.3601
0.94	0.72	0.05	0.01	-0.7627	1.4830
0.66	0.004	0.05	0.01	-0.0021	6.6007
0.66	0.05	0.05	0.01	-0.0264	6.6094
0.66	0.94	0.05	0.01	-0.8750	0.6251
0.66	0.72	0.00	0.01	-0.7181	0.5682
0.66	0.72	0.10	0.01	-0.6028	1.5667
0.66	0.72	0.15	0.01	-0.5164	1.5442
0.66	0.72	0.05	0.00	-0.6659	0.9911
0.66	0.72	0.05	0.05	-0.6648	-18.9197
0.66	0.72	0.05	0.10	-0.6637	-38.8305
0.66	0.72	0.05	0.15	-0.6625	-58.7413

5. Conclusions

The main findings of the present study corresponding to cooling of the plate in both the cases are:

- As the Schmidt number increases, the concentration decreases.
- The temperature decreases with an increase in the radiation absorption coefficient in both the cases. The temperature increases with an increase of heat source parameter in the case of (i) but it decreases in the case of (ii).
- An increase in Grashof number for heat and mass transfer or permeability parameter leads to an increase in the velocity.
- An increase in the magnetic field parameter or angle ϕ leads to a deceleration of the fluid motion.
- The temperature and velocity decrease with an increase in *Pr* in the case of uniform concentration and temperature.
- As *Gr* or *Gm* or *Q* or Q_1 or *k* increases, the skin-friction coefficient increases while it decreases as *Sc* or *M* or ϕ increases. As radiation absorption coefficient increases, the Nusselt number increase in the case of (i) but it decreases in the case of (ii). Further, the concentration, temperature and velocity increased in the case of constant heat and mass flux is greater than that in the case of uniform concentration and temperature.

The trend is just reversed in the case of heating of the plate in both the cases.

It is interesting to note that the magnitude of the velocity is equal in both the cases of heating and cooling of the plate. That is, they are mirror images of each other.

Table 3. Skin friction for cooling of the plate ($Gr > 0$, $Gm > 0$)

Gr	*Gm*	*Sc*	*Pr*	*Q*	Q_1	*M*	*K*	ϕ	Case (i)	Case (ii)
10	5	0.66	0.72	0.05	0.01	5	0.5	π/6	7.2855	13.8573
15	5	0.66	0.72	0.05	0.01	5	0.5	π/6	9.7163	18.4934
20	5	0.66	0.72	0.05	0.01	5	0.5	π/6	12.1471	23.1295
5	10	0.66	0.72	0.05	0.01	5	0.5	π/6	7.2785	13.8065
5	15	0.66	0.72	0.05	0.01	5	0.5	π/6	9.7024	18.3917
5	20	0.66	0.72	0.05	0.01	5	0.5	π/6	12.1262	22.9769
5	5	0.60	0.72	0.05	0.01	5	0.5	π/6	4.9293	9.8199
5	5	0.78	0.72	0.05	0.01	5	0.5	π/6	4.7185	8.3256
5	5	0.94	0.72	0.05	0.01	5	0.5	π/6	4.5594	7.5242
5	5	0.66	0.004	0.05	0.01	5	0.5	π/6	5.9827	3.9369
5	5	0.66	0.05	0.05	0.01	5	0.5	π/6	5.9238	44.0169
5	5	0.66	0.94	0.05	0.01	5	0.5	π/6	4.6238	7.8472
5	5	0.66	0.72	0.00	0.01	5	0.5	π/6	4.7916	8.7843
5	5	0.66	0.72	0.10	0.01	5	0.5	π/6	4.9364	9.8734
5	5	0.66	0.72	0.15	0.01	5	0.5	π/6	5.0624	11.1143
5	5	0.66	0.72	0.05	0.00	5	0.5	π/6	4.8407	9.1195

5	5	0.66	0.72	0.05	0.10	5	0.5	π/6	4.9800	10.1370
5	5	0.66	0.72	0.05	0.15	5	0.5	π/6	5.0496	10.6457
5	5	0.66	0.72	0.05	0.01	1	0.5	π/6	5.7280	11.2702
5	5	0.66	0.72	0.05	0.01	2	0.5	π/6	5.4649	10.6408
5	5	0.66	0.72	0.05	0.01	3	0.5	π/6	5.2359	10.1015
5	5	0.66	0.72	0.05	0.01	5	0.1	π/6	2.8043	4.8757
5	5	0.66	0.72	0.05	0.01	5	0.2	π/6	3.6628	6.6149
5	5	0.66	0.72	0.05	0.01	5	0.3	π/6	4.1967	7.7550
5	5	0.66	0.72	0.05	0.01	5	0.5	π/4	4.0541	7.4460
5	5	0.66	0.72	0.05	0.01	5	0.5	π/3	3.4038	6.0779
5	5	0.66	0.72	0.05	0.01	5	0.5	π/2	2.5149	4.3156

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