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Effects of Radiation on Free Convection Non-Darcy Flow along Non-isothermal Vertical Wall Embedded in a Porous Medium with Heat Generation

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***Abstract* - This work presents a numerical study to simulate the effect of thermal radiation on natural convection non-Darcy flow along non-isothermal vertical plate embedded in a porous medium with heat generation. Similarity solution is used to convert the governing differential equations from its dimensional form to its dimensionless form. Finite difference method is used to convert the dimensionless governing differential equations of the problem to its numerical form, and then it's programmed by using Fortran language. The work of the program is tested by making a comparison between present work and previously published work, and the result of the comparison is good, after that the program is run to give the results related to this study. Dimensionless velocity and temperature profiles as well as local Nusselt number are presented and discussed in detail for various values of involved parameters. From this result it can infer that the raise in the power law index of variable wall temperature, radiation parameter, and radiation parameter but in presence of heat generation enhances the amount of heat transfer. The increase in the Forchheimer parameter, Rayleigh number, and heat generation parameter lead to lessen the amount of heat transfer.**

Keywords: Natural convection, Thermal radiation, Porous medium, Vertical wall, Heat generation.

NOMENCLATURE

c	Specific heat of fluid (J /kg. K)
f	Dimensionless stream function
g	Gravitational acceleration (m.s^{-2})
K	Permeability of porous medium (m^2)
Nu_x	Local Nusselt number
P	Pressure (N/m^2)
q'''	Heat generation (W/m^3)
q_r	Radiative heat flux (W)
R	Radiation parameter
Ra_d	Rayleigh number depend on pore diameter
T	Fluid temperature (K)
(u, v)	Velocity components in the x and y directions respectively (m.s^{-1})
X	Coordinate along the plate (m)
y	Coordinate normal to the plate (m)
	Greek symbols
α	Equivalent thermal diffusivity ($m^2.s^{-1}$)
υ	Kinematic viscosity ($m^2.s^{-1}$)
ρ	Fluid density (kg. m^{-3})
β	Thermal expansion coefficient (K^{-1})
η	Similarity variable
ψ	Stream function
θ	Dimensionless temperature
χ	Mean absorption coefficient
σ	Stefan-Boltzmann constant

I. INTRODUCTION

Radiation effects on natural convection flow are significant in projects of space technology and applications that involving high temperature. There are broad industrial and engineering applications for porous materials. They are used in heat sinks, mechanical energy absorbers, catalytic reactors that are used in the exhaust of internal combustion machines, heat exchangers and filters used in cooling devices, especially those that use ice water (chillers) and electrical separators that are used in high capacities and reactor cores. In Nuclear field porous materials are used as an environment for cell development in bioreactors. Based on applications and importance of porous materials, many scientific studies either experimental or theoretical have attempted to explain the phenomena of flow and heat transfer in porous media since the nineteenth century by Darcy [2].

Kaviany and Mittal [9] studied the heat transfer by natural convection from a vertical constant-temperature plate immersed in a highly permeable porous medium. Murthy and Singh [10] investigated the effect of thermal dissipation (viscous dissipation) by viscosity on the natural convection along an equal-temperature vertical wall immersed in a saturated porous medium. Hossain et al.[11]studied the effect of radiation on the natural convection flow of an incompressible fluid along a vertical porous plate of uniform temperature with uniform suction of the fluid . Murthy and Singh [12] analyzed the effect of the lateral flow of mass and thermal dispersion on the natural convection over a vertical plate immersed in a saturated porous medium.

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Hung and Chen [13] studied heat transfer by natural convection along an impermeable vertical wall with a variable heat flux and the wall is immersed in a saturated thermally stratified porous medium. Mohammadien and EL-amin[14]investigated the effect of thermal dissipation and thermal radiation on the natural convection over a flat vertical plate immersed in a porous medium saturated with fluid. Grosan and Pop [15] studied the natural convection along a flat vertical plate with a variable surface temperature and immersed in a porous medium saturated with a non-Newtonian fluid. EL-hakiem and EL-amin [16] presented a study to show the effect of radiation and lateral mass flux (suction or injecting) on the natural convection along a vertical plate immersed in a porous medium saturated with fluid.

Ali [17] analyzed the effect of mass flux on the adjacent layers and heat transfer by natural convection over a hot vertical plate immersed in a saturated porous medium with heat generation. Ibrahim [18] studied the irregular natural convection flow of a viscous incompressible fluid in the presence of thermal radiation and chemical interaction along a vertical plate with heat generation. Uddin and Harmand[19]investigated the effect of non-uniform heat transfer by natural convection of a nano fluid along a vertical plate immersed in a porous medium. Haroui et al. [20] studied the double diffusion (heat and mass) by natural convection over a hot vertical plate immersed in a porous medium with the presence of Soret effect and a variable heat source.

Beg et al.[21] analyzed the flow in the adjacent layer of a Newtonian fluid along a vertical plate immersed in a porous medium in the presence of partial slip. Neagu [22] studied the transfer of heat and mass by natural convection adjacent a vertical permeable wall with the stability of heat flux and concentration. Hsu et al. [23] studied the magnetic hydrodynamic effect (MHD) on the natural convection over a vertical permeable plate immersed in a porous medium with heat generation. In this work it will be study the problem of effect of thermal radiation on natural convection non-Darcy flow over variable vertical wall temperature in a porous medium with the action of heat generation.

II. MATHEMATICAL FORMULATION

Consider the problem of impermeable vertical wall immersed in a porous medium saturated with fluid as shown in Figure (1) and on the assumption that the fluid flow is non-Darcy, two-dimensional, laminar and incompressible, and that the fluid properties are constant except for the density term in the momentum equation (buoyancy term) which will be considered variable according to the Boussinesq approximation and that the fluid is viscous and the solid porous material is non-deformable and in thermal equilibrium with the fluid. The surface temperature of the wall is considered variable and undergoes the power law which will be explained later. Inertia effect will be taken as the non-Darcy effect in the momentum equation. According to the above assumptions the governing equations for fluid flow and heat transfer in porous media can be represented by:

2.1 Continuity Equation [24,2]

Since the flow is two-dimensional and stable and the fluid is incompressible, the continuity equation can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

Where u is the component of velocity in the x direction and v is the component of velocity in the y direction

2.2 Momentum Equation [24,2]

The equation for conservation of momentum in the x direction can be represented by:

$$u=\frac{-K}{\mu}\left(\frac{\partial p}{\partial x}+\rho g\right)-\frac{c\sqrt{K}}{\upsilon}u^2 \qquad (2)$$

Also, the equation for conservation of momentum in the y direction is given by:

$$v=\frac{-K}{\mu}\left(\frac{\partial p}{\partial y}\right)-\frac{c\sqrt{K}}{\upsilon}v^2 \qquad (3)$$

Within the boundary layer it can be assumed $\frac{\partial}{\partial x}<<\frac{\partial}{\partial y}$ and $v<<u$ so $v=0$, $\frac{\partial v}{\partial x}=0$. By eliminating pressure term from equations (2) and (3) by using cross differentiation it can be write the momentum equation in the following final form:

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$$\frac{\Box}{K}\frac{\partial u}{\partial y}+\frac{\Box}{\sqrt{K}}\frac{c}{\upsilon}\frac{\partial u^{2}}{\partial y}+\frac{\partial \rho g}{\partial y}=0 \qquad (4)$$

2.3 Energy Equation [24,14,17]

The energy conservation equation for the problem under study can be written as follows:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^{2} T}{\partial y^{2}}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{q'''}{\rho c_p} \qquad (5)$$

Where the thermal radiation q_r and internal heat generation q''' can be represented by:

Equation of radiative heat flux [14]

$$q_r=\frac{-4\sigma}{3\chi}*\frac{\partial T^{4}}{\partial y} \qquad (6)$$

Equation of internal heat generation [17]

$$q'''=A^{*}k\frac{(T_w-T_\infty)}{x^{2}}Ra_x e^{-\eta} \qquad (7)$$

2.4 Boussinesq Approximation [2]

$$\rho=\rho_\infty[1-\beta(T-T_\infty)] \qquad (8)$$

The similarity solution will be used for the purpose of solving the problem, so some non-dimensional variables will be used to convert the above equations from their dimensional form to their non-dimensional form, as shown below:

2.5 Boundary conditions

At $y=0: v=0,\ T=T_\infty+ax^{n}$

At $y=\infty: u=0\ \ T=T_\infty$ (9)

2.6 Dimensionless Variables [1]

$$\eta=Ra_x^{\frac{1}{2}}\frac{y}{x},$$

$$\psi=f(\eta)\,\alpha\,Ra_x^{\frac{1}{2}},\quad u=\frac{\partial\psi}{\partial y},\quad v=-\frac{\partial\psi}{\partial x},\quad \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty} \qquad (10)$$

Where Ra_x is the modified Rayleigh number, $Ra_x=\frac{Kg\beta\,(T_w-T_\infty)x}{\alpha\,\upsilon}$.

After substituting the above dimensionless variables in the above equations the following system of dimensionless equations can be obtained:

2.7 Dimensionless Momentum Equation

$$f''+2f_0 f' f'' Ra_d-\theta'=0 \qquad (11)$$

Where $f_0=\frac{\sqrt{K}\,\alpha}{d}\frac{c}{\upsilon}$, represents the structural and thermophysical properties of the porous medium and $Ra_d=\frac{Kg\beta\,(T_w-T_\infty)d}{\alpha\,\upsilon}$, represent relative intensity of buoyancy force.

2.8 Dimensionless Energy Equation

$$\theta''+\frac{4}{3}R\,\theta''+\frac{1}{2}f\theta'(n+1)-n\,f'\theta+A^{*}e^{-\eta}=0 \qquad (12)$$

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Where R=$\frac{4\sigma T^3{}_\infty}{\chi k}$ represent the radiation parameter and A^* represent heat generation parameter.

2.9 Dimensionless Boundary Conditions

At η =0 $f(0)$ =0, $\theta(0)$ =1

At η =η_{max} , $f'(\eta_{max})$ =0, $\theta(\eta_{max})$ =0 (13)

The velocity components become

$$u = \frac{\alpha}{x} f'(\eta)\, Ra_x \qquad (14)$$

$$v = \frac{-\alpha}{2x} Ra_x^{\frac{1}{2}} [\, f(n+1) + f'\eta(n-1)\,] \qquad (15)$$

The heat transfer rate is given by

$$q_w = -\,k \frac{\partial T}{\partial y}|_{y=0} - q_r \qquad (16)$$

And the local Nusselt number can be represented by

$$Nu_x Ra_x^{\frac{-1}{2}} = -\theta'(0)\,[\,1 + \tfrac{4}{3}\,R\,] \qquad (17)$$

III. NUMERICAL SCHEME

The system of ordinary differential equation (11) to (13) is solved numerically by finite difference approximation. The central difference approximation is used to represent the first and second derivatives. Fortran Language is used to program the system of equations on the computer. A uniform step size of Δη=0.05 is employed. The boundary conditions with η ⟶ ∞is replaced by η_{max} where η_{max} is a sufficiently large value that satisfies the solution, therefore η_{max} =14 is adopted in this study. Furthermore, five decimal accuracy is used. Numerical computations were carried out for $0 \le n \le 2$, $0 \le f_0 \le 0.5$, $0 \le Ra_d \le 5$, $0 \le R \le 4$, and $0 \le A^* \le 1$. For more information about the numerical solution it is recommended to review reference [26].

IV. RESULT AND DISCUSSION

In order to check the validity of the program results a comparison has been made with previously published work on special case of the problem.

Table 1 presents the values of the local Nusselt number for the case of Darcy flow for different values of the power law of the surface temperature of the vertical plate (n) for present work and results obtained by Hsiehet al. [25]the comparison were found to be good. T is comparison gives complete reliability of the computer program. Specific values of the variables have been taken and entered into the program for the purpose of studying their impact on the velocity profile, temperature profile, and local Nusselt number. The values of n were taken from 0 to 2 with an increment of 0.5 and the values of $f_0$were taken from 0 to 0.5 with an increment of 0.1, while Ra_d values ranged from 0 to 5 with an increments of 1, R has been studied for the values from 0 to 4 with an increment of 1, and the values ofA^* was changed from 0 to 1 with an increment of 0.5 .

The effect of increasing the value of the power law index of the wall surface temperature n on the dimensionless velocity that plotted against the similarity variable (η) is illustrated in Figure (2).we noticed that the increase in the wall temperature with the increase in the value of the parameter (n) leads to a decrease in the dimensionless flow velocity. Figure (3) shows the behaviour of the dimensionless temperature against the similarity variable (η). It is clear that there is an increase in the temperature gradient with an increase in the value of the parameter (n). The effect of increasing the parameter (n) on the local Nusselt number is illustrated in Figure (4). From the figure it can be see that the value of the local Nusselt number is increased. This increase is due to the aforementioned effects on the dimensionless velocity and temperature.

Increasing the Forchheimer parameter leads to an increase in inertia, which means an increase the obstruction of the porous medium. Figure (5) represents the effect of increasing the Forchheimer parameter on the dimensionless velocity that plotted against the similarity variable (η). The figure shows a decrease in the dimensionless flow velocity next to the surface as the Forchheimer parameter increases,

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while the fluid velocity increases away from the surface due to the inertia effect. Figure (6) shows the effect of increasing the Forchheimer parameter on the dimensionless temperature where it can be notice a slight increase in temperature as well as the thickness of the thermal boundary layer, and thus a decrease in the temperature gradient. Figure (7) shows the effect of the Forchheimer parameter on the local Nusselt number. It is clear from the figure that there is a decrease in the local Nusselt number with the increase in the Forchheimer parameter.

Figure (8) represents the effect of increase Rayleigh number Ra_d on dimensionless velocity of the fluid It shows that there is a decrease in the velocity of the fluid near the wall and then occurs slight increase in the velocity of fluid away from the wall as the Rayleigh number increase. Figure (9) depicts the effect of increasing the Rayleigh number on the dimensionless temperature. It is clear that there is a slight increase in fluid temperature, and a decrease in the temperature gradient. Figure (10) illustrates that the value of the local Nusselt number decrease with an increase in the Rayleigh number value, which means a decrease in the rate of heat transfer.

Figure (11) illustrates the effect of increasing the thermal radiation parameter on the dimensionless velocity that plotted against the similarity variable (η). It is clear from the figure that increasing the thermal radiation parameter leads to an increase in the dimensionless velocity of the fluid and a decrease in the velocity gradient. Figure (12) represents the effect of increasing the thermal radiation parameter on the dimensionless temperature. It can be see that there is an increase in the dimensionless temperature, and hence increase in the thickness of the thermal boundary layer, and a decrease in the temperature gradient. The effect of thermal radiation parameter on the local Nusselt number is presented in Figure (13). The local Nusselt number raise highly with the increase in the value of the thermal radiation parameter R. which indicates a high heat transfer and this means that the local Nusselt number is sensitive to the increase in the value of thermal radiation parameter.

The effect of heat generation parameter A^{*}on the dimensionless velocity of the fluid is depicted in Figure (14). It can be seen from Figure (14) that the increase in heat generation leads to an increase in the fluid velocity. Figure (15) present the relationship between the heat generation parameter and the dimensionless temperature of the fluid and it shows an increase in the dimensionless temperature, with the increase in the heat generation parameter. The effect of heat generation parameter on the local Nusselt number is illustrated in Figure (16). It is noticed that the value of the local Nusselt number decrease with the increase in the value of the heat generation parameter.

Finally the effect of the heat radiation parameter R in the presence of heat generation parameter on the velocity and temperature profiles as well as local Nusselt number are shown in Figures 17 to 19 .

Figure (17) shows that increasing the thermal radiation parameter in the presence of heat generation leads to a noticeable increase in the fluid velocity The effect of the thermal radiation parameter in the presence of heat generation on the dimensionless temperature is presented in Figure(18) The figure shows an increase in the dimensionless temperature and an increase in the thickness of the thermal boundary layer thickness with the increase in the thermal radiation parameter The effect of the thermal radiation parameter in the presence of heat generation on the local Nusselt number is depicted in Figure (19). It can be noticed from the figure that the value of the local Nusselt number raises with the increase in the value of the thermal radiation parameter.

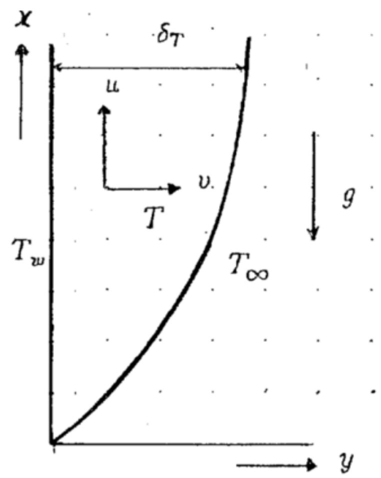

Figure 1: The flow model and the physical coordinate system

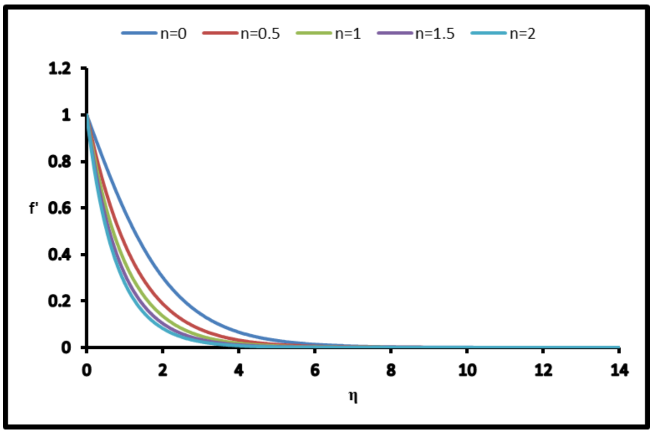

Figure 2: Effects of (n) on the velocity profile when: f_0=0, R=0, Rad=0, A*=0

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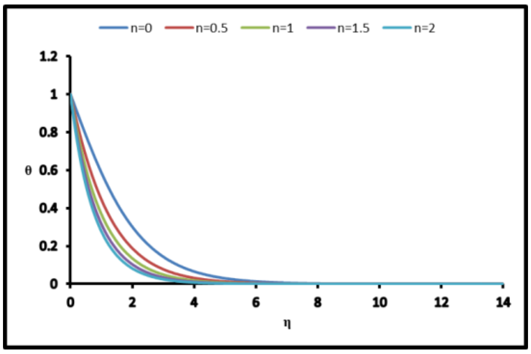

Figure 3: Effects of (n) on the temperature profile when: f_0=0, R=0, Rad=0, A*=0

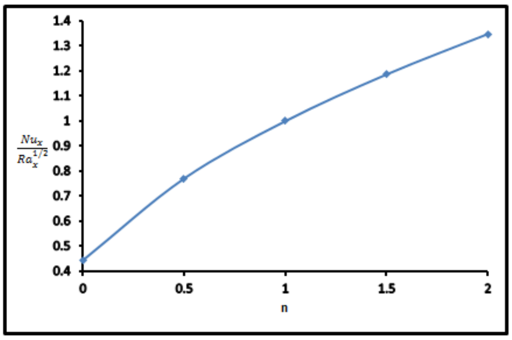

Figure 4: Effects of (n) on the local Nusselt number when: f_0=0, Rad=0, A*=0, R=0

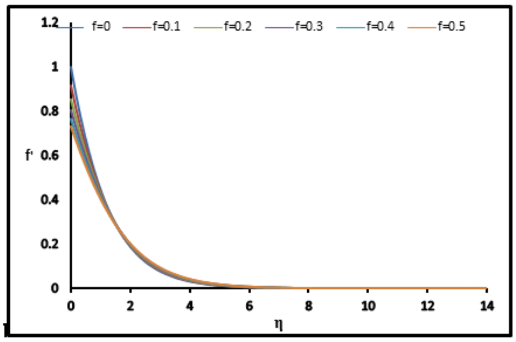

Figure 5: Effects of (f_0) on the velocity profile when: n=0.5, Rad=1, A*=0, R=0

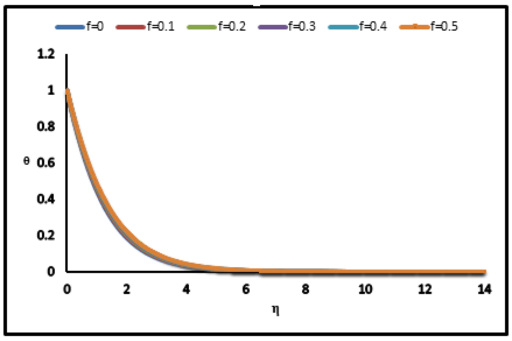

Figure 6: Effects of (f_0) on the temperature profile when: n=0.5, Rad=1, A*=0, R=0

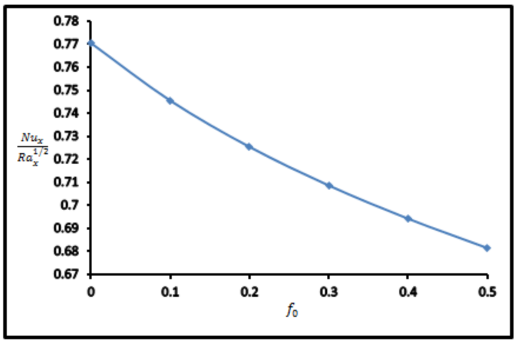

Figure 7: Effects of (f_0) on the local nusselt number when: n=0.5, Rad=1, A*=0, R=0

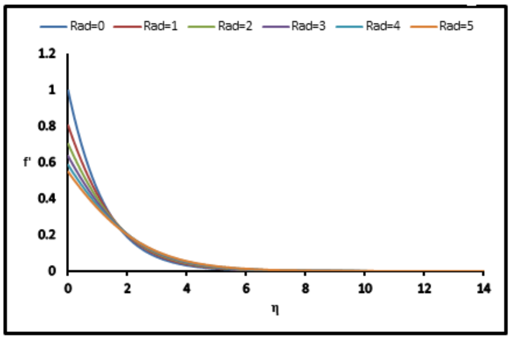

Figure 8: Effects of Rayleigh number on the velocity profile when: n=0.5, f_0=0.3, A*=0, R=0

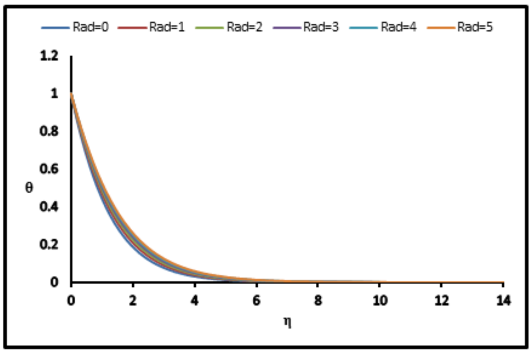

Figure 9: Effects of Rayleigh number on the temperature profile when: n=0.5, f_0=0.3, A*=0, R=0

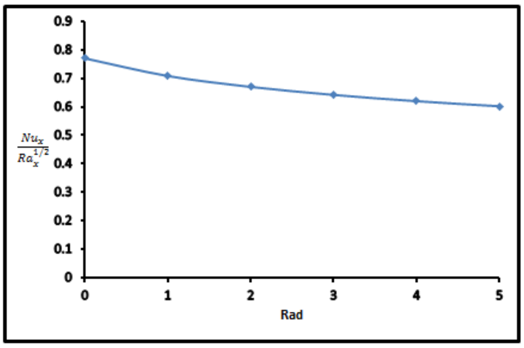

Figure 10: Effects of Rayleigh number on the local nusselt number when: n=0.5, f_0=0.3 , A*=0, R=0

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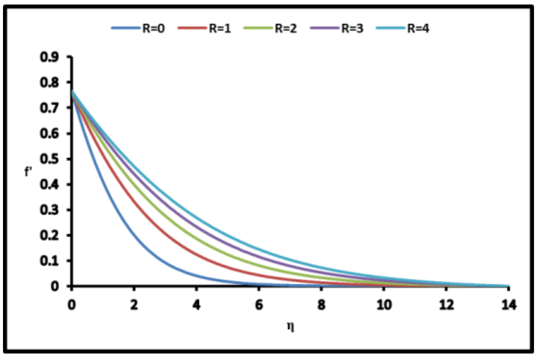

Figure 11: Effects of (R) on the velocity profile when: n=0.5, f_0=0.2, Rad=2 A*=0

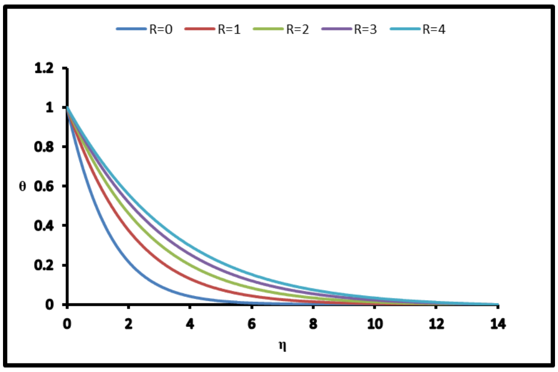

Figure 12: Effects of(R) on the temperature profile when: n=0.5,f_0=0.2, Rad=2 A*=0

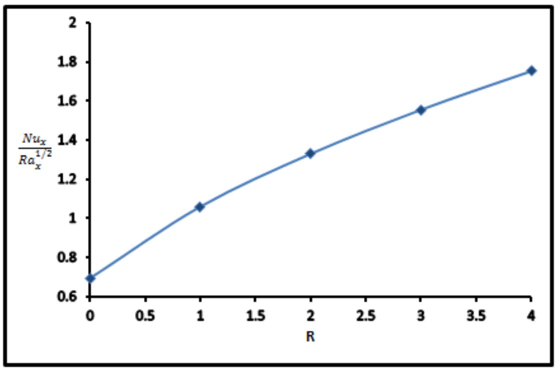

Figure 13: Effects of (R) on the local nusselt number when: n=0.5, f_0=0.2, Rad=2 A*=0

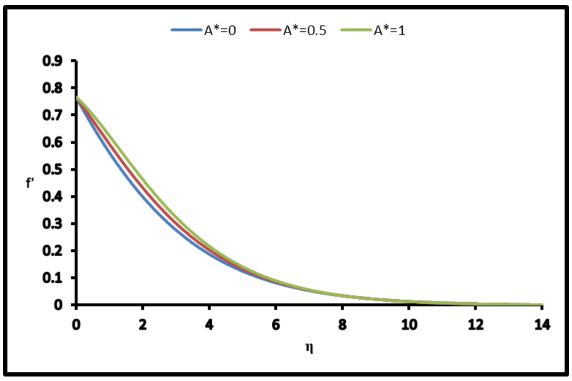

Figure 14: Effects of (A*) on the velocity profile when: n=0.5,f_0=0.2 , Rad=2 R=2

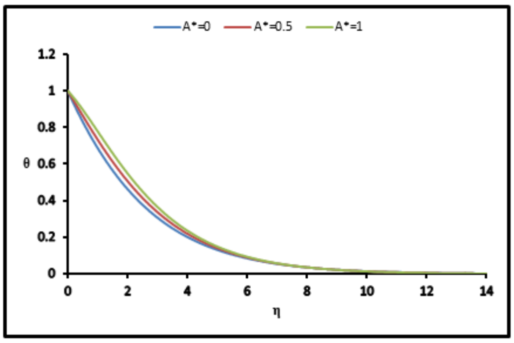

Figure 15: Effects of (A*) on the temperature profile when: n=0.5, f_0=0.2, Rad=2 R=2

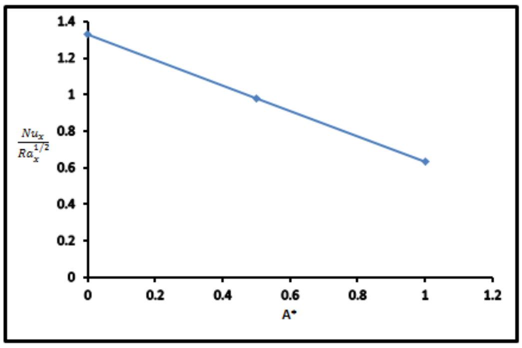

Figure 16: Effects of (A*) on the local nusselt number when: n=0.5, f_0=0.2, Rad=2 R=2

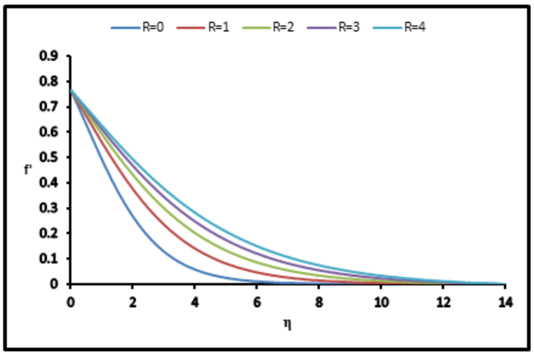

Figure 17: Effects of (R) on the velocity profile in the presence of (A*) when: n=0.5,f_0=0.2, Rad=2 A*=0.5

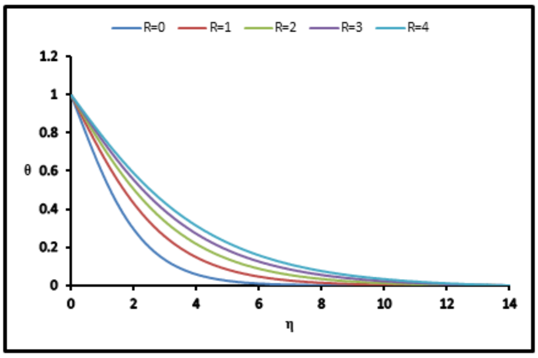

Figure 18: Effects of (R) on the temperature profile in the presence of (A*) when: n=0.5, f_0=0.2, Rad=2 A*=0.5

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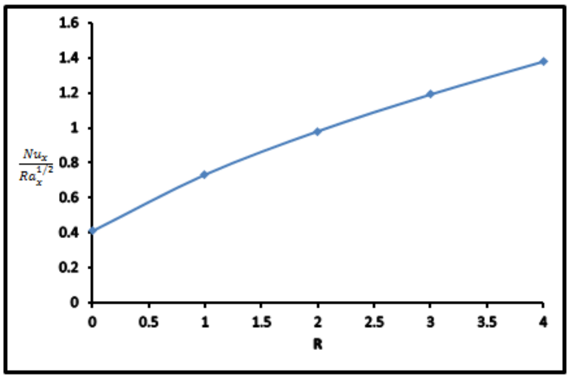

Figure 19: Effects of (R) on the local nusselt number in the presence of (A*) when: n=0.5, f_0=0.2, Rad=2 A*=0.5

Table 1 comparison between the local Nusselt number values obtained by Hsieh et al.[25] , and the present study for different values of (n).

n	Hsieh al. [25]	Present results
0	0.4438	0.4439
0.5	0.7704	0.7705
1.0	1.0000	1.0000

V. CONCLUSIONS

A numerical study has been done to study the effect of radiation on free convection Non-Darcy flow along Non-isothermal vertical wall embedded in a porous medium with heat generation. Similarity solution is used to convert the governing differential equations from its dimensional form to its dimensionless form. Finite difference method is used to convert the dimensionless governing differential equations of the problem to its numerical form, and then it's programmed by using Fortran language. The accuracy of the result is checked by making a comparison with previously published work on special case of the problem. From the above results it can be concluded that:

1. The boost in the values of power law index, radiation parameter, and radiation parameter in the presence of heat generation parameter leads to increase the value of local Nusselt number.
2. Raises in the values of Forchheimer parameter, Rayleigh number, and heat generation parameter causes a decrease in the local Nusselt number.

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