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THE EFFECT OF RADIATION AND BUOYANCY ON BOUNDARY LAYERS INDUCED BY CONTINUOUS SURFACES STRETCHED WITH RAPIDLY DECREASING VELOCITIES

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ABSTRACT– *The present study is devoted to study the influence of radiation and buoyancy on heat and mass transfer characteristics of the self-similar boundary layer flows induced by continuous surfaces having a prescribed variable surface temperature and stretched with rapidly decreasing power law velocities. The effects of mixed convection flow with suction in the presence of a quiescent fluid medium of constant temperature are considered. Rosseland approximation is used to describe the radiative heat flux in the energy equation. The transformed governing equations are solved numerically and the velocity and temperature profiles as well as the local Nusselt number and skin friction coefficient are presented. Results show that the effect of radiation is to keep the molten mass away from the slot warmer, reduces the friction factor and increases the heat transfer rate compared to the case in the absence of radiation.*

KEYWORDS: *mixed convection, stretched surfaces, power law, radiation*

1. INTRODUCTION

Continuously moving surface [1] through another quiescent medium has many applications in several industrial manufacturing processes such as hot rolling, wire drawing, metal and polymer extrusion, crystal growing, continuous casting, glass fiber and paper production, drawing of plastic films, etc. Both the kinematics of stretching and the heat transfer during such processes have a decisive influence on the quality of the final products.

Suction or injection of a stretched surface was introduced by Erickson et al. [2] and Fox et al. [3] for uniform surface velocity and temperature and by Gupta and Gupta [4] for linearly moving surface. Chen and Char [5] have studied the suction and injection on a linearly moving plate subject to uniform wall temperature and heat flux and the more general case using a power law velocity and temperature distribution at the

NOMENCLATURE

b	Strength of surface temperature, (K/m^n)
c	Constant defined in equation (5), $((m/s)/m^{(m-1)/2})$
C_{fx}	Local skin friction coefficient, Eqn. (19)
c_p	Specific heat capacity at constant pressure, (J/kg K)
C_t	Temperature difference Coefficient; Eqn. (14)
f	Dimensionless stream function, (-)
g	Gravitational accleration, (m/s^2)
Gr_x	Local Grashof number, $(g\beta(T_w - T_\infty)x^3/\nu^2)$
k	Thermal coductivity coefficient, (W/m K)
m	Velocity exponent, (-)
n	Temperature exponent, (-)
Nu_x	Local Nusselt number, Eqn. (21)
Pr	Prandtl number, (ν/α)
q_r	Radiative heat flux, (W/m^2)
q''	Surface heat flux, (W/m^2)
Re_x	Local Reynolds number, Eqn. (24)
R_1	Radiation-fluid parameter, Eqn. (13)
s	Parameter [=0, +1, or –1]
T	Temperature, (K)
u	Velocity component in the x direction, (m/s)
u_w	Stretching velocity, (m/s)
u_0	Strength of stretching velocity, $((m/s)/m^m)$
v	Velocity component in the y direction, (m/s)
v_w	Suction velocity, (m/s)
x	Coordinate in the direction of surface motion, (m)
y	Coordinate in the direction normal to surface motion, (m)
α	Thermal diffusivity, (m^2/s)
β	Volumetric coefficient of thermal expansion, (1/K)
χ	Mean absorption coefficient, (1/m)
η	Similarity space variable, Eqn. (8)
λ	Buoyancy parameter, $(s\ Gr_x / Re_x^2)$
μ	Viscosity coefficient, (kg/m s)
ν	Kinematic viscosity, (m^2/s)
θ	Dimensionless temperature, Eqn. (9)
ρ	Fluid density, (kg/m^3)
σ	Stefan-Boltzmann constant, $(W/m^2\ K^4)$
τ	Shear stress, (N/m^2)

SUBSCRIPTS

w	Surface conditions.
∞	Conditions away from the surface.

SUPERSCRIPTS

$'$	Derivative with respect to η

surface was studied by Ali [6]. Magyari et al. [7] reported analytical and computational solutions when the surface moves with rapidly decreasing velocities using the self-similar method.

The effects of buoyancy force were neglected in Refs. [2-7]. However, Ali [1], Ali and Al-Yousef [8], and Lin et al. [9] have taken it into consideration.

Abo-Eldhab and El Gendy [10] investigated the problem of heat transfer characteristics in an electrically conducting fluid near an isothermal sheet under the combined effect of buoyancy and radiation in the presence of a uniform free stream of constant velocity and temperature.

El-Hakiem and El-Amin [11] presented a boundary-layer analysis to study the influence of thermal radiation and lateral mass flux on non-Darcy natural convection over a vertical flat plate in a fluid saturated porous medium.

The kinematics driving the conditions of the real processes have been modeled in most cases by different power-law variations of the stretching velocity $u_w(x) = u_0.x^m$. The stretching surface is considered as a permeable surface with a lateral mass flux velocity $v_w(x) = c.x^{(m-1)/2}$ where $c < 0$ corresponds to the suction ,$c > 0$ to the injection of the fluid and $c = 0$ corresponds to immpermeable wall.

The rapidly decreasing stretching velocities $m < -1$ should be relevant for several industrial manufacturing processes e.g. the drawing of plastic films from a viscous molten mass. In this case the film just issuing from the slot (x = small) is hot and thus rapidly stretching. For increasing *x* however, the film hardens in the colder ambient progressively and, as a consequence, the local stretching velocity $u_w(x) \propto x^m$ decreases rapidly. This case has been invistigated by Magyari et al. [7] and it was obtained that, for $m < -1$, the boundary layers equation admit self-similar solutions only if a lateral suction applied and the dimensionless suction velocity $f_w < 0$ must be strong enough.

Ali [1] indicated that similarity solutions exist only when the condition $n = 2m - 1$ is satisfied.

The present paper illustrates the dependence of the heat and fluid flows induced by surfaces stretching with rapidly decreasing velocities in the presence of both radiation and buoyancy force on the physical parameters f_w, m, n ,Pr, C_t and R_1.

2. FORMULATION OF THE PROBLEM

Consider the steady, two-dimensional motions of mixed convection boundary layer laminar flow from a vertically moving surface with suction or injection at the surface. For incompressible viscous fluid environment with constant properties using Boussinesq approximation, the equations governing the convective flow are, [1] and [11]

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

Momentum:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = sg\beta(T - T_\infty) + \nu\frac{\partial^2 u}{\partial y^2} \tag{2}$$

Energy:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho\, c_p}\frac{\partial q_r}{\partial y} \tag{3}$$

subjected to the following boundary conditions:

$$\left.\begin{array}{l} u(x,0) = u_w(x), u(x,\infty) = 0, v(x,0) = v_w(x) \\ T(x,0) = T_w(x), \quad T(x,\infty) = T_\infty \end{array}\right\} \tag{4}$$

where,

$$u_w(x) = u_0 x^m, v_w(x) = cx^{(m-1)/2}, T_w(x) - T_\infty = bx^n \tag{5}$$

The x coordinate is measured along the moving surface from the point where the surface originates, and the y coordinate is measured normal to it, as shown schematically in **Fig. 1**, u and v are the x and y components of the velocity field respectively, and $v_w(x)$ represents the lateral injection/suction velocity of the ambient fluid and s is a dummy parameter stands for 0, +1, -1. As it was indicated in [1], equations (1-3) admit similarity solutions only if the stretching velocity $u_w(x)$ and the temperature difference $T_w(x) - T_\infty$ as functions of the wall coordinate x are either of the power law type or of the exponential form. In the present paper, the power law type is used for the case of $m < -1$ of the rapidly decreasing power law velocities when the buoyancy force exists. The range of the stretching velocities should be relevant for the drawing of plastic films from a viscous molten mass [1].

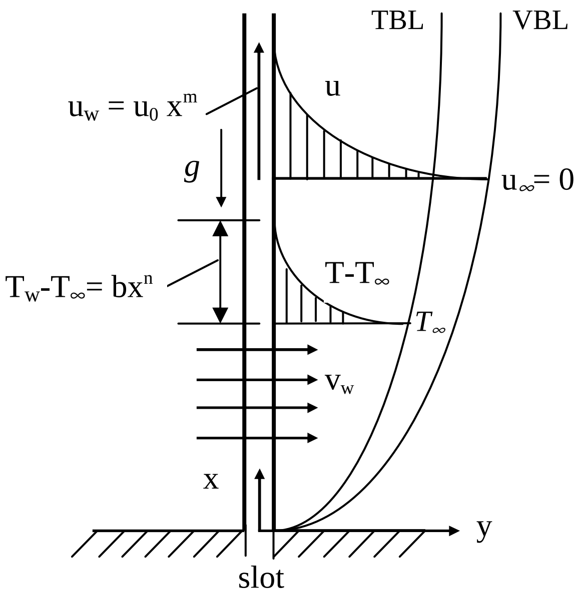

Figure 1. Schematic of the induced boundary layers close to a vertical surface moving with rapidly decreasing velocity with suction.

Diffusion (Differential) approximation model used for an optically thick medium is used for equating the radiative heat flux in the y direction; q_r. In order to reduce the complexity of the problem and to provide a means of comparison with future studies which will employ a more detailed representation for the radiative heat flux, the optically thick radiation limit is considered in the present analysis. Thus, the radiative heat flux term on the right hand side of equation (3) is simplified by using the Rosseland approximation (Sparrow and Cess [12]), and is as follows:

$$q_r = -\frac{4\sigma}{3\chi}\frac{\partial T^4}{\partial y} \tag{6}$$

This approximation is valid only for a gray, intensive absorbing and emitting but non-scattering optically thick medium [13]. The radiative heat flux in the x-direction is considered negligible in comparison with that in the y direction (Sparrow and Cess[12]). The great advantage of Rosseland type approximations, i.e., diffusion approximations is the fast computation time achieved by including the thermal radiation as a correction in the energy equation [13].

The usual similarity solutions arise when, [1]

$$u(x,y) = u_0 x^m f'(\eta), \qquad T(x,y) - T_\infty = bx^n \theta(\eta) \tag{7}$$

$$\eta = \left[(|m|-1)u_0/(2\nu)\right]^{1/2} x^{\frac{m-1}{2}} y \tag{8}$$

$$\theta = \frac{T - T_\infty}{T_w - T_\infty} \tag{9}$$

$$v(x,y) = \left[\frac{((m+1)\nu\ u_0)}{-2}\right]^{1/2} x^{\frac{m-1}{2}}\left[f(\eta) + \frac{m-1}{m+1}\eta f'(\eta)\right] \tag{10}$$

where f' and θ are the dimensionless velocity and temperature respectively, and η is the similarity variable.

Subistitution in the governing equations gives rise to the following two-point boundary-value problem.

$$f''' - ff'' + \frac{2m}{m+1}[f']^2 - \frac{2}{m+1}\lambda\theta = 0 \tag{11}$$

$$\theta'' - \Pr\ (f\theta' - \frac{2n}{m+1}f'\theta) + R_1\left((C_t + \theta)^3\theta'\right)' = 0 \tag{12}$$

Where, in analogy to [11], the radiation-fluid and temperature difference parameters; R_1 and C_t are defined as,

$$R_1 = \frac{1}{\alpha.\rho\ c_p}\left(\frac{16\sigma}{3\chi}\right)(T_w - T_\infty)^3 \tag{13}$$

$$C_t = \frac{T_\infty}{T_w - T_\infty} \tag{14}$$

The last term between brackets in equation (12) is due to the radiation and R_1 serves as the radiation-fluid parameter. When $R_1 = 0$, this means that the radiation is neglected and the governing equations reduce to the problem of self-similar boundary layer flow induced by continuous surfaces stretched with power law velocities given by Ali [1] for mixed convection flow in the absence of radiation.

Similarly, the last term in equation (11) is due to the buoyancy force represented by the buoyancy parameter, $\lambda = sGr_x / Re_x^2$, Gr_x is local Grashof number $\left[= g\beta(T_w - T_\infty)x^3/\nu^2\right]$. When s = 0 implies λ = 0 and means that the buoyancy forces are neglected and the governing equations in the absence of radiation reduce to the forced convection limit given by Magyari et al. [7] for m < -1. However, when $\lambda \to \infty$ free convection should be demoninated. It should be mentioned that, when s = +1 (λ > 0) the last term in equation (11) is positive means that the x-axis points upwards in the direction of stretching the hot surface such that the stretched induced flow and the thermal bouyant flow assist each other (assisting flow, **Fig. 1**). On the other hand, when s = -1 (λ < 0) means that the x-axis points vertically downwards in the direction of stretching the hot surface but in this case the stretching induced flow and the thermal bouyant flow oppose each other (opposing flow). Equations (10-11) subject to the boundary conditions:

$$f(0) = f_w, \quad f'(0) = 1, \quad f'(\infty) = 0 \tag{15}$$

$$\theta(0) = 1, \quad \theta(\infty) = 0 \tag{16}$$

In driving the second of the boundary conditions given by equation (15), the horizontal injection or suction speed, v_w must be a function of the distance (for $m \neq 1$) from the leading edge. Consequently, v_w for m < -1 is given by:

$$v_w(x) = \left[\frac{(|m-1|\nu\ u_0)}{2}\right]^{1/2} x^{-\frac{|m|+1}{2}} f(0) \tag{17}$$

The quantity f(0) = f_w will be referred to as the dimensionless suction/injection velocity. Therefore, $f_w = 0$ corresponds to an impermeable surface, $f_w < 0$ (c < 0) to suction and $f_w > 0$ (c > 0) to lateral injection of the fluid through a permeable surface.

The shearing stress at the vertical surface is given by:

$$\tau_w = \left(\mu \frac{\partial u}{\partial y}\right)_{y=0} = \mu\left[\frac{(|m|-1)\ u_0}{2\nu}\right]^{1/2} u_0 x^{\frac{3m-1}{2}} f''(0) \tag{18}$$

The local skin friction coefficient; C_{fx}, takes the form:

$$C_{fx} = \frac{\tau_w}{\frac{1}{2}\rho(u_{y=0})^2} = \left[\frac{2(|m|-1)\nu}{u_0}\right]^{1/2} x^{\frac{|m|-1}{2}} f''(0) \tag{19}$$

The surface heat flux, q'', and local Nusselt number, Nu_x are given by,

$$q'' = -k\left(\frac{\partial T}{\partial y}\right)_{y=0} - \frac{4\sigma}{3\chi}\frac{\partial T^4}{\partial y}\ \Big)_{y=0} \tag{20}$$

$$\mathrm{Nu}_x = \frac{q''}{\left(T_w - T_\infty\right)}\frac{x}{k} = -\left[\frac{\left(|m|-1\right)u_0}{2\nu}\right]^{1/2}\left\{1+\frac{16\sigma}{3k\chi}\left[T_\infty + Bx^n\theta(\eta)\right]^3\right\} x^{\frac{1-|m|}{2}}\theta'(\eta) \tag{21}$$

The local skin friction coefficient and Nusselt number can be expressed in dimensionless form independent of surface coordinate x as follows:

$$C_{fx}\sqrt{\mathrm{Re}_x} = \left[2\left(|m|-1\right)\right]^{1/2} f''(0) \tag{22}$$

$$\mathrm{Nu}_x / \sqrt{\mathrm{Re}_x} = -\left[\frac{\left(|m|-1\right)u_0}{2\nu}\right]^{1/2}\left\{1+R_1\left[Ct+\theta(0)\right]^3\right\}\theta'(0) \tag{23}$$

Where,

$$\mathrm{Re}_x = \frac{\rho u_{y=0}\, x}{\mu} = \frac{u_0}{\nu}x^{1-|m|} \tag{24}$$

is the local Reynolds number.

The set of transformed governing equations; (11, 12) are solved using a fourth order Runge-Kutta method of numerical integration.

In order to start a solution, the values of boundary conditions at $\eta = 0$ are substituted and integration must be carried out up to some large η to see if the boundary conditions at infinity are satisfied.

3. RESULTS AND DISCUSSION

Equations (11) and (12) were solved numerically for (m, n) = (-2, -5*)* and = (-6, -13) satisfying the necessary condition for existing of similar solution for mixed convection flow induced by continuous surfaces stretched with power law velocities which is $n = 2m - 1$.

Numerical results of the coefficient of friction and Nusselt number variations for various values of f_w,, λ, Pr in the absence of radiation (R_1=0.0) showed the same trends remarked by Ali [1] for the same values of m and n. Samples of these results, which are presented in table 1, shows agreement with those presented by Ali [1].

Samples of the resulting velocity and temperature profiles for (m, n) = (-2, -5*)* and = (-6, -13), f_w =-3.0 and λ=0.03 for various values of R_1 in **figures 2** and **3** and for various values of C_t in **figures 4** and **5**.

It may be concluded from **figures 2** and **4** that radiation-fluid parameter and temperature difference coefficient have no appreciable effect on velocity profile. However, **figures 3** and **5** illustrate that temperature profiles thicken as the radiation-fluid parameter and temperature difference coefficient increase. This matches findings presented in [10].

Figure 3 shows that the slope of the temperature distribution at the surface with the presence of radiation is always negative and the heat is always transferred from the surface to the ambient fluid. Also, it shows that radiation damps the overshoot in temperature near the surface.

Table 1: Values of $\left|C_{fx}\sqrt{\mathrm{Re}_x}\right|$ and $\mathrm{Nu}_x/\sqrt{\mathrm{Re}_x}$ for selected values of m, n, λ, f_w , Pr and R_1=0.0.

m, n	f_w	λ	Pr	Parameter	m, n	f_w	λ	Pr	$\left\|C_{fx}\sqrt{\mathrm{Re}_x}\right\|$
m =-2, n =-5	-5	1.8	1.0	$\mathrm{Nu}_x/\sqrt{\mathrm{Re}_x}$ = 2.5148	m = -2, n = -5	-7	-1.0	1.0	9.8293
		-0.45		$\left\|C_{fx}\sqrt{\mathrm{Re}_x}\right\|$ = 6.6296	m=-6, n=-13	-5	-2.45		15.3961
	-3	-0.03		$\left\|C_{fx}\sqrt{\mathrm{Re}_x}\right\|$ = 2.7048		-3	0.03	0.1	7.2814

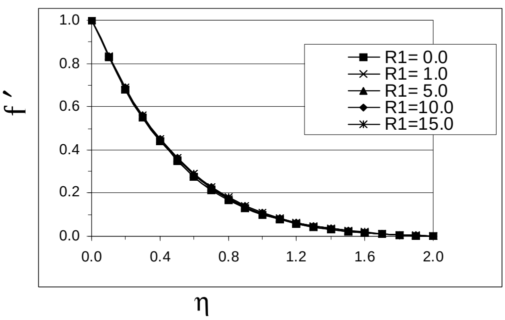

Figure 2: Dimensionless velocity variation for different R_1 (m=-2.0, n=-5.0, Pr=1.0, f_w=-3.0, λ=0.03, C_t=0.3)

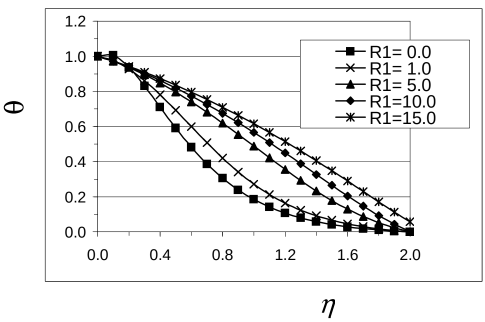

Figure 3 Dimensionless temperature variation for different R_1 (m=-2.0, n=-5.0, Pr=1.0, f_w=-3.0, λ=0.03, C_t=0.3)

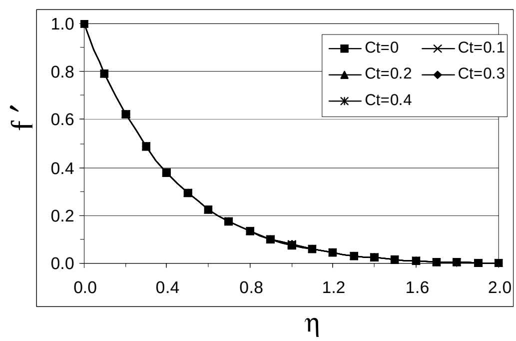

Figure 4 Dimensionless velocity variation for different C_t (m=-6.0, n=-13.0, Pr=1.0, f_w=-3.0, λ=0.03, R_1=1.0)

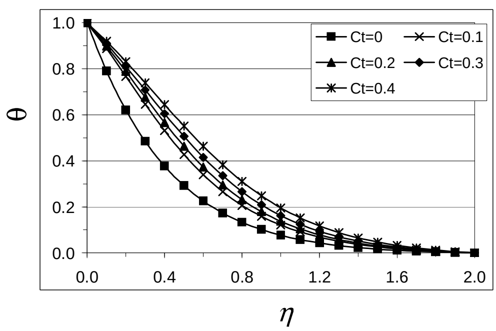

Figure 5 Dimensionless temperature variation for different C_t (m=-6.0, n=-13.0, Pr=1.0, f_w=-3.0, λ=0.03, R_1=1.0)

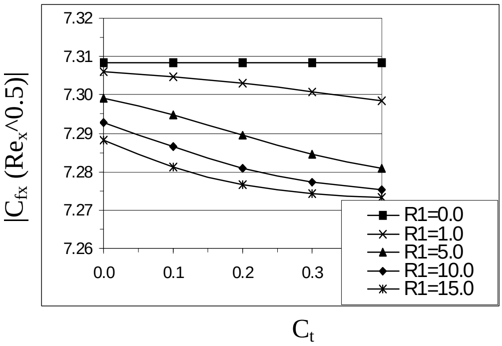

Figure 6: Variation of absolute value of C_{fx} with C_t for different R_1 (m = -6, n = -13, f_w = -3, Pr =1.0, λ = 0.03)

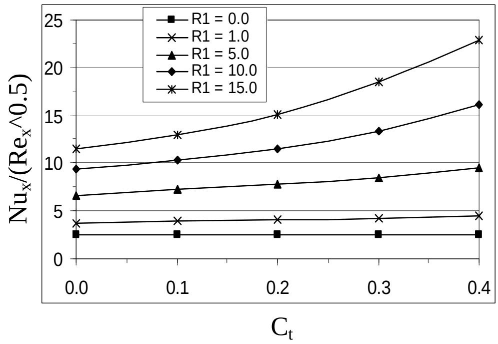

Figure 7: Nu_x variation with C_t for different R_1 (m = -C_t n = -13, f_w = -3, Pr = 1.0, λ = 0.03)

Figures 6, 7 and **Table 2** show the effect of temperature difference coefficient on friction coefficient and Nusselt number for various radiation-fluid parameter and specific values of m, n, f_w , Pr and λ . It may be remarked that increasing either or both of R_1 and C_t, while holding other parameters constant, reduces friction factor and increases heat transfer rate. This matches findings tabulated and presented by El-Hakiem and El-Amin [11]. However, friction factor is less affected. Decreasing friction factor enhances the deformability of the viscous molten mass.

Figures 8 and **9** illustrate the effect of Prandtl number on friction factor and heat transfer from the surface for various values of R_1, m = -6, n = -13, f_w = -3.0, λ = 0.03 and C_t = 0.1. It may be remarked that both friction factor and Nusselt number increase as Pr increases. With analogy to Fig. 6, it may be observed that friction factor is less affected.

Table 2: Values of $\left|C_{fx}\sqrt{\mathrm{Re}_x}\right|$ and $\mathrm{Nu}_x/\sqrt{\mathrm{Re}_x}$ for selected values of R_1 and C_t with m=-6, n=-13, f_w=-3, Pr=1.0, λ=0.03.

R_1	C_t	$\left\|C_{fx}\sqrt{\mathrm{Re}_x}\right\|$	$\mathrm{Nu}_x/\sqrt{\mathrm{Re}_x}$	R_1	C_t	$\left\|C_{fx}\sqrt{\mathrm{Re}_x}\right\|$	$\mathrm{Nu}_x/\sqrt{\mathrm{Re}_x}$
0.0	-	7.3085	2.5756				
1.0	0.0	7.3060	3.6884	10.0	0.0	7.2929	9.3643
	0.1	7.3048	3.9100		0.1	7.2867	10.2603
	0.2	7.3031	4.1152		0.2	7.2810	11.4616
	0.3	7.3001	4.2980		0.3	7.2772	13.3846
	0.4	7.2983	4.4621		0.4	7.2752	16.1198
5.0	0.0	7.2990	6.6612	15.0	0.0	7.2881	11.5504
	0.1	7.2947	7.2225		0.1	7.2814	12.9438
	0.2	7.2896	7.7554		0.2	7.2766	15.1237
	0.3	7.2846	8.4434		0.3	7.2741	18.4715
	0.4	7.2808	9.4944		0.4	7.2731	22.9393

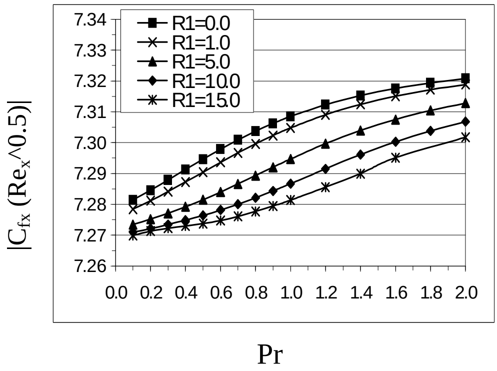

Figure 8: Effect of Pr on absolute value of C_{fx} for various values of R_1 (m = -6, n = -13, f_w = -3.0, λ = 0.03, C_t = 0.1)

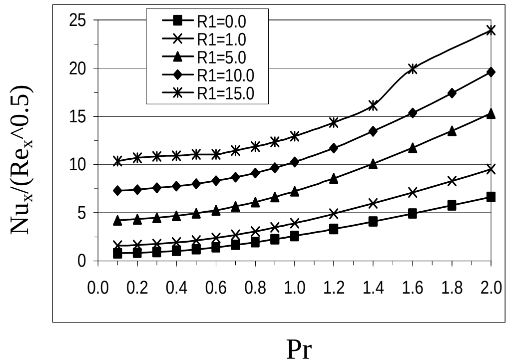

Figure 9: Effect of Pr on Nu_x for various values of R_1 (m = -6, n = -13, f_w = -3.0, λ = 0.03, C_t = 0.1)

It may be remarked that the effect of radiation on heat transfer increases with increasing Prandtl number.

Two counter effects may be remarked from observing **Figs. 3, 6** and **9**. While **Figs. 3** and **6** illustrate that the effect of radiation is to increase the temperature for the points having traverse position from slot centerline (y >0, i,e. η >0) compared to the corresponding values with no radiation, , thus keeps the molten mass warmer compared to the case in the absence of radiation and reduces the possibility of its hardening due to colder ambient and enhances its deformability, thus reduces the possibility of its hardening due to colder ambient.. However, **figure 9** illustrates that the heat transfer from the stretched surface increases with radiation.

4. CONCLUDING REMARKS

In this work, the equations governing the effect of radiation and mixed convection on a vertically moving surface stretched with rapidly decreasing velocities were solved for different values of suction velocity parameter; f_w , buoyancy parameter; λ , Prandtl number; Pr, temperature difference coefficient; C_t and radiation-fluid parameter; R_1.

As it was expected, temperature profiles thicken as the radiation-fluid parameter and temperature difference coefficient increase.

It may be concluded that the effect of radiation is to keep the molten mass away from the slot warmer, reduces the friction factor and increases the heat transfer rate compared to the case in the absence of radiation.

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تأثير الإشعاع والطفو على الطبقة الجدارية الناتجة عن شد الأسطح المستمرة بسرعة متناقصة

هذا البحث مكرس لدراسة تأثير الإشعاع والطفو على خصائص الانتقال الحراري والكتلي للسريان خلال الطبقة الجدارية الناتجة عن شد الأسطح المستمرة ذات درجات حرارة متغيرة معرفة سلفا بسرعة تتناقص بقوى أسية. وتم دراسة الانتقال الحراري بالحمل المختلط في وجود شفط ومائع (وسط) محيط ساكن ودرجة حرارة ثابتة. استخدم تقريب (***Rosseland***) لتمثيل الفيض الحراري في معادلة الطاقة. تم إيجاد حلول عددية للمعادلات التفاضلية وتمثيل معادلات السرعة ودرجة الحرارة ومعدل الانتقال الحراري ومعامل الاحتكاك السطحي. تشير النتائج أن تأثير الإشعاع هو الإبقاء على سخونة الكتلة المسالة بعيدا عن الشق و تقليل الاحتكاك السطحي وزيادة معدل الانتقال الحراري مقارنة بالحالة التي تخلو من الإشعاع.