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Natural convection flow of a viscous fluid with viscosity inversely proportional to linear function of temperature from a vertical wavy cone

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Abstract — Free convection over an isothermal vertical wavy cone immersed in a fluid with variable viscosity is studied in this paper. We consider the boundary-layer regime where the Grashof number is very large and assume that the wavy surfaces have O(1) amplitude and wavelength. Using the appropriate variables, which reduce the wavy cone to a flat one, the basic equations are transformed to nonsimilar boundary-layer equations. These equations are then solved numerically using a very efficient implicit finite-difference method known as Keller box scheme. Detailed results for the streamlines, isotherms, reduced skin friction and heat transfer rates for a selection of parameter sets consisting of the viscosity parameter, wavy surface amplitude, half cone angle and Prandtl number. © 2001 Éditions scientifiques et médicales Elsevier SAS

natural convection / temperature dependent viscosity / vertical wavy cone

Nomenclature

a	amplitude of the wavy surface of the cone	
C_f	skin friction coefficient	
g	acceleration due to the gravity	$m \cdot s^{-2}$
Gr	Grashof number	
L	characteristic length associated with the wavy surface	m
Nu	local Nusselt number	
p	pressure	
Pr	Prandtl number	
r	local radius of the flat surface of the cone	
T	temperature	K
u, v	velocity components along (x, y)-axes	
x, y	Cartesian coordinates along and normal to the flat surface of the cone, respectively	

Greek symbols

α	thermal diffusivity	$m^2 \cdot s^{-1}$
β	coefficient of thermal expansion	K^{-1}
γ	constant defined by equation (7)	
ε	constant defined by equation (15)	
$\mu(T)$	variable viscosity	$kg \cdot m^{-1} \cdot s^{-1}$
$\sigma(x)$	surface geometry function	
θ	reduced temperature	
ξ, η	pseudo-similarity variables	
ρ	density	$kg \cdot m^{-3}$
ϕ	cone half-angle	rad
ψ	stream function	

Subscripts

w	wall conditions
∞	ambient conditions
x	differentiation with respect to x

1. INTRODUCTION

Roughened surfaces are encountered in several heat transfer devices such as flat plate solar collectors and flat plate condensers in refrigerators. Larger scale surface nonuniformities are encountered, for example, in cavity wall insulating systems and grain storage containers. The only papers to date which study the effects of

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such nonuniformities on the vertical convective boundary layer flow of a Newtonian fluid are those of Yao [1], and Moulic and Yao [2, 3]. Hossain and Pop [4] investigated the magnetohydrodynamic boundary layer flow and heat transfer from a continuous moving wavy surface, while the problem of free convection flow from a wavy vertical surface in the presence of a transverse magnetic field was studied by Hossain et al. [5]. On the other hand, Rees and Pop [6–8] investigated the free convection boundary layer induced by vertical and horizontal surfaces exhibiting small-amplitude waves embedded in a porous medium. Recently, Hossain and Rees [9] have considered the combined effects of thermal and mass diffusion on the natural convection flow of a viscous incompressible fluid from a vertical wavy surface. The effects of waviness of the surface on the heat flux and mass flux distributions in combination with the species concentration for a fluid with Prandtl number equal to 0.7 has been studied in that paper. Very recently, Pop and Na [10] studied both the constant wall temperature and constant heat flux distribution on the natural convection flow over a vertical wavy frustum of a cone.

In all the above studies the authors assumed that both the viscosity and thermal conductivity of the fluids are constant throughout the flow regime. However, it is known that these physical quantities may change significantly with temperature, see the review article by Kakaç [11]. When the effect of variable viscosity is included in the analysis, Gary et al. [12] and Mehta and Sood [13] have found that the flow characteristics substantially change compared with the constant viscosity case. Further, Hady et al. [14], Kafoussias and Williams [15], and Kafoussias et al. [16] have studied the effects of variable viscosity on the mixed convection flow from a vertical flat plate in the region near the leading edge using the local nonsimilarity method. Very recently, Hossain et al. [17, 18] have considered the natural convection from a vertical wavy surface and a truncated cone placed in a fluid with variable viscosity when the viscosity is inversely proportional to a linear function of temperature, a model which was proposed by Ling and Dybbs [19]. Also, Hossain and Munir [20], and Hossain et al. [21] investigated the mixed convection flow over a vertical flat plate and, respectively, the forced convection flow over a wedge for a similar law of variable viscosity.

In this paper we focus our attention on the free convection boundary layer over a vertical wavy cone driven by a uniform wall temperature immersed in a fluid with a temperature dependent viscosity using the same model as proposed by Ling and Dybbs. The transformed boundary-layer equations are solved numerically using a very efficient finite-difference method known as Keller box scheme [22]. Consideration is given to the situation where the buoyancy forces assist the flow for various values of the viscosity variation parameter, ε, with the Prandtl number $Pr = 0.7$ and 7.0, which are appropriate for air and water, respectively. The results allow us to predict the different flow and heat transfer characteristics that can be observed when the relevant parameters are varied.

2. FORMULATION OF THE PROBLEM

Consider the steady laminar free convection of a viscous and incompressible fluid along a vertical wavy cone as shown in *figure 1*, where the viscosity of the fluid depends on its temperature. We assume that the wavy surface of the cone is described by the equation

$$\hat{y}_{\mathrm{w}} = \hat{\sigma}(\hat{x}) = \hat{a}\sin(\pi\hat{x}) \tag{1}$$

where $\hat{a}$ is the amplitude of the wavy surface of the cone. We also assume that the temperature of the cone surface is held constant at T_{w} and is higher than the temperature T_∞ of the ambient fluid. The boundary layer analysis outlined below allows $\hat{\sigma}(\hat{x})$ to be arbitrary, but our detailed numerical work will assume that the wavy surface is described by equation (1).

The governing equations are the continuity, Navier–Stokes and the energy equations in two-dimensional Cartesian coordinates $(\hat{x}, \hat{y})$ (see *figure 1*). Under the

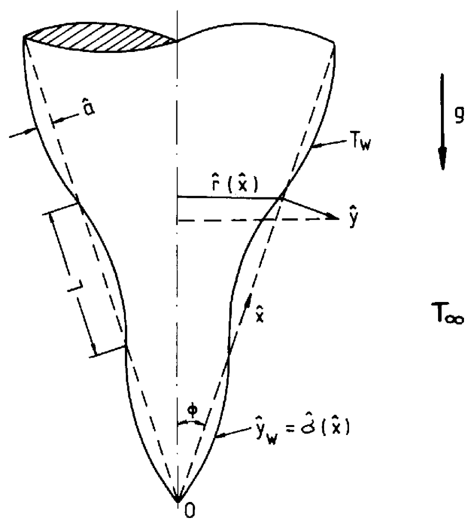


Figure 1. Physical model and coordinate system.

usual Boussinesq approximation, these equations can be written as

$$\frac{\partial(\hat{r}\hat{u})}{\partial\hat{x}}+\frac{\partial(\hat{r}\hat{v})}{\partial\hat{y}}=0 \tag{2}$$

$$\hat{u}\frac{\partial\hat{u}}{\partial\hat{x}}+\hat{v}\frac{\partial\hat{u}}{\partial\hat{y}}=-\frac{1}{\rho}\frac{\partial\hat{p}}{\partial\hat{x}}+\nabla(\mu\nabla\hat{u}) + g\beta(T-T_\infty)\cos\phi \tag{3}$$

$$\hat{u}\frac{\partial\hat{v}}{\partial\hat{x}}+\hat{v}\frac{\partial\hat{v}}{\partial\hat{y}}=-\frac{1}{\rho}\frac{\partial\hat{p}}{\partial\hat{y}}+\nabla(\mu\nabla\hat{v}) - g\beta(T-T_\infty)\sin\phi \tag{4}$$

$$\hat{u}\frac{\partial T}{\partial\hat{x}}+\hat{v}\frac{\partial T}{\partial\hat{y}}=\alpha\nabla^2 T \tag{5}$$

where $(\hat{u},\hat{v})$ are the velocity components along the $(\hat{x},\hat{y})$ axes, ∇^2 is the two-dimensional Laplacian operator, g is the acceleration due to gravity, ρ is the density, α is the thermal diffusivity, β is the coefficient of thermal expansion, $\mu(T)$ is the viscosity of the fluid depending on the temperature T, ϕ is the cone half-angle and $\hat{r}$ is the local radius of the flat surface of the cone, which is given by

$$\hat{r}=\hat{x}\sin\phi \tag{6}$$

Out of the many forms of viscosity variation, which are available in the literature, we will consider only the following form proposed by Ling and Dybbs [19]:

$$\mu=\frac{\mu_\infty}{1+\gamma(T-T_\infty)} \tag{7}$$

where γ is a constant and μ_∞ is the viscosity of the ambient fluid. The boundary conditions for equations (2)–(5) are

$$\begin{aligned}&\hat{u}=0,\quad \hat{v}=0,\qquad T=T_\mathrm{w}\quad \text{at } \hat{y}=\hat{y}_\mathrm{w}=\hat{\sigma}(\hat{x})\\ &\hat{u}=0,\quad T=T_\infty,\quad p=p_\infty\quad \text{as } \hat{y}\to\infty\end{aligned} \tag{8}$$

We now introduce the following non-dimensional boundary-layer variables:

$$\begin{aligned}&x=\frac{\hat{x}}{L},\quad y=\frac{\hat{y}-\hat{\sigma}}{L}Gr^{1/4}\\ &r=\frac{\hat{r}}{L},\quad p=\frac{L^2}{\rho\nu_\infty^2}Gr^{-1}\hat{p}\\ &u=\frac{\rho L}{\mu_\infty}Gr^{-1/2}\hat{u},\quad v=\frac{\rho L}{\mu_\infty}Gr^{-1/4}(\hat{v}-\sigma_x\hat{u})\\ &\theta=\frac{T-T_\infty}{T_\mathrm{w}-T_\infty},\quad a=\frac{\hat{a}}{L},\quad \sigma(x)=\frac{\hat{\sigma}(x)}{L}\\ &\sigma_x=\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{x}}=\frac{\mathrm{d}\sigma}{\mathrm{d}x},\quad Gr=\frac{g\beta(T_\mathrm{w}-T_\infty)\cos\phi}{\nu_\infty^2}L^3\end{aligned} \tag{9}$$

where L is the characteristic length associated with the wavy surface of the cone, ν_∞ $(=\mu_\infty/\rho)$ is the reference kinematic viscosity and Gr is the Grashof number. Introducing transformations (9) into equations (2)–(5) and after ignoring terms of small orders in Gr, we obtain the following boundary layer equations:

$$\frac{\partial(ru)}{\partial x}+\frac{\partial(rv)}{\partial y}=0 \tag{10}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+Gr^{1/4}\sigma_x\frac{\partial p}{\partial y}+\frac{(1+\sigma_x^2)}{1+\varepsilon\theta}\frac{\partial^2 u}{\partial y^2} - \frac{\varepsilon(1+\sigma_x^2)}{(1+\varepsilon\theta)^2}\frac{\partial\theta}{\partial y}\frac{\partial u}{\partial y}+\theta \tag{11}$$

$$\sigma_x\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)-\sigma_{xx}u^2 = -Gr^{1/4}\frac{\partial p}{\partial y}+\frac{\sigma_x(1+\sigma_x^2)}{1+\varepsilon\theta}\frac{\partial^2 u}{\partial y^2} - \frac{\varepsilon\sigma_x(1+\sigma_x^2)}{(1+\varepsilon\theta)^2}\frac{\partial\theta}{\partial y}\frac{\partial u}{\partial y}-\theta\tan\phi \tag{12}$$

$$u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}=\frac{1}{Pr}\left(1+\sigma_x^2\right)\frac{\partial^2\theta}{\partial y^2} \tag{13}$$

with the boundary conditions (8) becoming

$$\begin{aligned}&u=0,\quad v=0,\qquad \theta=T_\mathrm{w}\quad \text{at } y=0\\ &u=0,\quad T=T_\infty,\quad p=0\quad \text{as } y\to\infty\end{aligned} \tag{14}$$

In equations (11) and (12) the viscosity variation parameter ε is defined as

$$\varepsilon=\gamma(T_\mathrm{w}-T_\infty) \tag{15}$$

From equation (7) it can clearly be seen that the dimensionless viscosity μ/μ_∞ lies in the range between $1/(1+\varepsilon)$ and 1; its value decreasing with increasing temperature when $\varepsilon>0$. Equation (11) indicates that the pressure gradient along the y direction is $O(Gr^{-1/4})$, which implies that the lowest order pressure gradient along x direction can be determined from the inviscid flow solution. However, this pressure gradient is zero since there is no externally induced free stream. On the other hand, equation (12) shows that $Gr^{1/4}\partial p/\partial y$ is O(1) and is determined by the left-hand side of this equation. Thus, the elimination of $\partial p/\partial y$ between equations (11) and (12) leads to

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1+\sigma_x^2}{1+\varepsilon\theta}\frac{\partial^2 u}{\partial y^2}-\frac{\varepsilon(1+\sigma_x^2)}{(1+\varepsilon\theta)^2}\frac{\partial u}{\partial y}\frac{\partial \theta}{\partial y}+\left(\frac{1-\sigma_x\tan\phi}{1+\sigma_x^2}\right)\theta-\frac{\sigma_x\sigma_{xx}}{1+\sigma_x^2}u^2 \quad (16)$$

If we now introduce the nonsimilar variables:

$$\psi=x^{3/4}rf(x,\eta),\quad \eta=x^{-1/4}y \qquad \theta=\theta(x,\eta),\quad r=x\sin\phi \quad (17)$$

where ψ is the stream function which is defined according to $u=\partial\psi/\partial y$ and $v=-\partial\psi/\partial x$, equations (10), (13) and (16) become

$$\frac{1+\sigma_x^2}{1+\varepsilon\theta}f'''+\frac{7}{4}ff''-\left(\frac{1}{2}+\frac{x\sigma_x\sigma_{xx}}{1+\sigma_x^2}\right)f'^2-\frac{\varepsilon(1+\sigma_x^2)}{(1+\varepsilon\theta)^2}\theta' f''+\left(\frac{1-\sigma_x\tan\phi}{1+\sigma_x^2}\right)\theta=x\left\{f'\frac{\partial f'}{\partial x}-f''\frac{\partial f}{\partial x}\right\} \quad (18)$$

$$\frac{1}{Pr}(1+\sigma_x^2)\theta''+\frac{7}{4}f\theta'=x\left(f'\frac{\partial\theta}{\partial x}-\theta'\frac{\partial f}{\partial x}\right) \quad (19)$$

along with the boundary conditions

$$f(x,0)=f'(x,0)=0,\quad \theta(0,x)=1 \qquad f'(x,\infty)=\theta(0,\infty)=0 \quad (20)$$

The quantities of physical interest are the skin friction and the rate of heat transfer which can be described in terms of the skin friction coefficient, C_f, and local Nusselt number, Nu, in the form:

$$C_f\left(\frac{Gr}{x}\right)^{1/4}=\frac{(1+\sigma_x^2)^{1/2}}{1+\varepsilon}f''(0,\xi) \quad (21)$$

$$Nu\left(\frac{Gr}{x}\right)^{-1/4}=-\left(1+\sigma_x^2\right)^{1/2}\xi^{3/4}\theta'(0,\xi) \quad (22)$$

3. RESULTS AND DISCUSSION

Equations (18) and (19) along with the boundary conditions (20) were solved numerically by the finite-difference method known as Keller box method. Since a good description of this method and its application to boundary-layer flow problems is given in the book by Cebeci and Bradshaw [23] as well as in many papers such as, for example, Hossain et al. [24], it will not be presented here. Results are given for the variable viscosity parameter $\varepsilon=0.0$ (constant viscosity), 0.5, 1.0 and 2.0; the amplitude parameter $a=0.0$ (flat cone) and 0.2 (wavy cone); Prandtl number $Pr=0.7$ (air) and 7.0 (water); cone half-angle $\phi=0°$ (flat plate), 30° and 45°. *Figures 2* and *3* illustrate the effect of the parameter ε on the development of streamlines and isotherms for a flat cone ($a=0.0$) and a wavy cone ($a\neq 0.0$), respectively. These figures clearly show the difference between the flow and heat transfer characteristics over a flat cone and a wavy one, respectively. For a wavy cone the isotherms

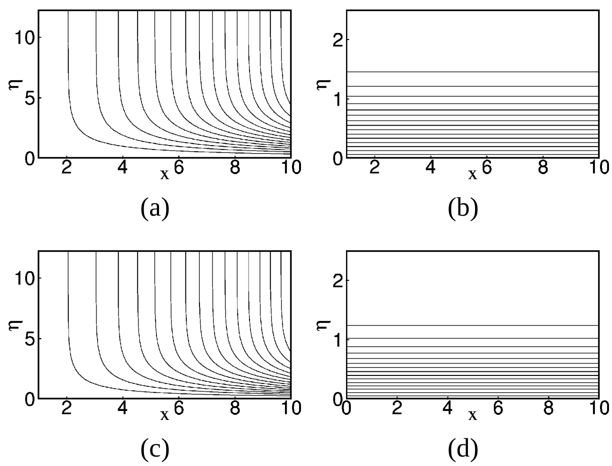


Figure 2. (a) Dimensionless streamlines for $\varepsilon=0.0$, $Pr=7.0$, $\alpha=0.0$ and $\phi=30°$. (b) Dimensionless isotherms for $\varepsilon=0.0$, $Pr=7.0$, $\alpha=0.0$ and $\phi=30°$. (c) Dimensionless streamlines for $\varepsilon=2.0$, $Pr=7.0$, $\alpha=0.0$ and $\phi=30°$. (d) Dimensionless isotherms for $\varepsilon=2.0$, $Pr=7.0$, $\alpha=0.0$ and $\phi=30°$.

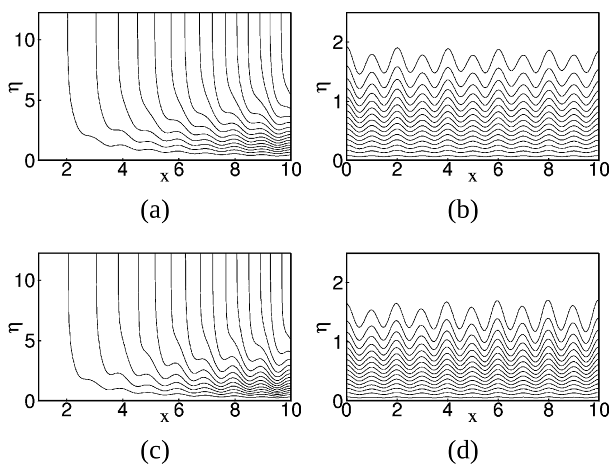
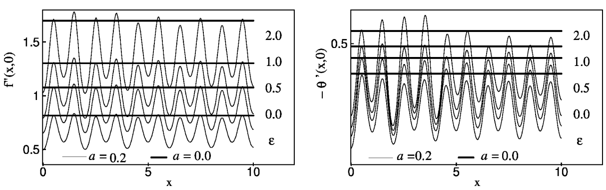
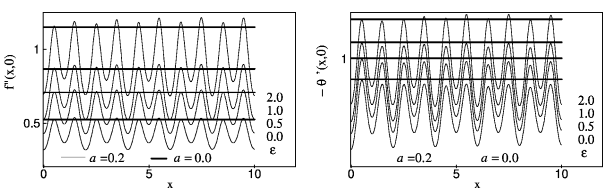


Figure 3. (a) Dimensionless streamlines for $\varepsilon=0.0$, $Pr=7.0$, $\alpha=0.2$ and $\phi=30°$. (b) Dimensionless isotherms for $\varepsilon=0.0$, $Pr=7.0$, $\alpha=0.2$ and $\phi=30°$. (c) Dimensionless streamlines for $\varepsilon=2.0$, $Pr=7.0$, $\alpha=0.2$ and $\phi=30°$. (d) Dimensionless isotherms for $\varepsilon=2.0$, $Pr=7.0$, $\alpha=0.2$ and $\phi=30°$.



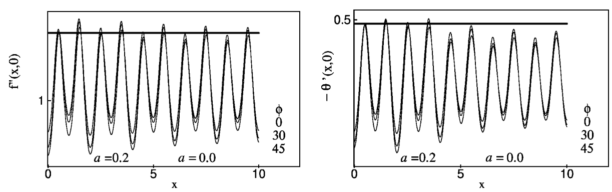
(a) (b)

Figure 4. Variation of the reduced skin friction $f''(x,0)$ (a) and reduced heat transfer $-\theta'(x,0)$ (b) with x for different values of ε with $Pr = 0.7$, $\phi = 30°$.



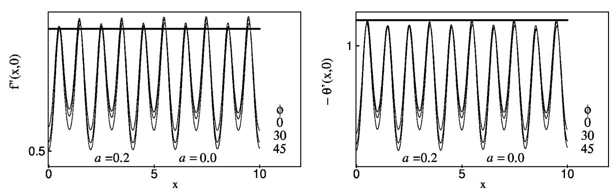
(a) (b)

Figure 5. Variation of the reduced skin friction $f''(x,0)$ (a) and reduced heat transfer $-\theta'(x,0)$ (b) with x for different values of ε with $Pr = 7.0$, $\phi = 30°$.



(a) (b)

Figure 6. Variation of the reduced skin friction $f''(x,0)$ (a) and reduced heat transfer $-\theta'(x,0)$ (b) with x for different values of ϕ with $Pr = 0.7$, $\varepsilon = 1.0$.



(a) (b)

Figure 7. Variation of the reduced skin friction $f''(x,0)$ (a) and reduced heat transfer $-\theta'(x,0)$ (b) with x for different values of ϕ with $Pr = 7.0$, $\varepsilon = 1.0$.

show a sinusoidal behavior, while for a flat cone these are parallel lines showing the dominant mode of heat transfer between the two configurations.

Variation of the reduced skin friction coefficient $f''(x,0)$ and reduced heat transfer $-\theta'(x,0)$ as a function of x are shown in *figures 4–7* for fluids with $Pr = 0.7$ and 7.0, and selected values of the parameters ε, a and ϕ. It is seen, as expected, that the values of $f''(x,0)$ and $-\theta'(x,0)$ are lower for a wavy cone than for a flat cone. This can be explained as follows. When the heated surface of the cone is not flat ($a \neq 0$), the component of the buoyancy force along the cone is reduced by a factor $(1 - \sigma_x \tan\phi)/(1 + \sigma_x^2)$, as shown in equation (18), from its maximum value of a flat cone. Consequently, the boundary layer thicknesses are locally smaller, and hence local rates of the skin friction coefficient $f''(x,0)$ and the heat transfer rate $-\theta'(x,0)$ are reduced. However, *figures 6* and *7* show that the changes are more pronounced for larger cone angles. Further, *figures 4* and *5* indicate that an increase in the variable viscosity parameter ε leads to an increase of the skin friction and heat transfer rates from the cone. For a wavy cone ($a \neq 0$) the skin friction and heat transfer rates are smaller than for a flat cone ($a = 0$). Since the thermal resistance increases as the fluid accumulates between the trough and crest, it will reduce the values of skin friction and heat transfer rates. Finally, we see from *figures 4–7* that the heat transfer rates increase with the increase of the Prandtl number Pr and viscosity parameter ε, and this is in agreement with the results reported by Kakaç [11] and Kafoussias et al. [16] for the corresponding problem of natural convection over a vertical flat plate immersed in a fluid of variable viscosity. Therefore, the net benefit of heat transfer of wavy surfaces is very significant and the application of a periodically corrugated wall for heat exchanger or solar collector is a sound approach.

4. CONCLUSIONS

In this paper a theoretical study of the laminar free convection boundary-layer heat transfer between a vertical wavy cone with a constant surface temperature and a fluid of variable viscosity has been done. New variables to transform the complex geometry into a simplex shape were used and a very efficient implicit finite-difference (Keller box) scheme was employed to solve the boundary-layer equations. It has been found that the effect of increasing the viscosity parameter ε is to increase the skin friction coefficient and heat transfer rate. It was also observed that the heat transfer rate increases with the increase of the Prandtl number and this is in agreement with the known results from the open literature. It is worth mentioning that the amplitude of the waves must be within an $O(Gr^{-1/4})$ range in order to balance the direct and indirect buoyancy forces. Strong enough curvature may produce flow separation, or rather, the flow develops a region of reverse flow at the surface of the wavy cone. A detailed study of this flow behavior was recently presented by Rees and Pop [7].

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