LOCAL HEAT TRANSFER FROM A YAWED WEDGE

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In this paper, the local heat transfer from the surface of an infinite yawed wedge, when the temperature of the main-stream is constant, is studied under two cases: (i) when the wall temperature is steady and the velocity of the main-stream is unsteady and (ii) when the wall temperature is unsteady and the velocity of the main-stream is steady. It is found that the local heat transfer depends on the wedge angle, the angle parameter and the yaw of the wedge. The behaviour with the yaw of the wedge is studied graphically. It is observed that the local heat transfer increases with the yaw of the wedge.

1. INTRODUCTION

The study of local heat transfer from swept wings has some importance in aerodynamics. In the boundary layer flow past yawed or swept back wings, there results a cross-flow due to the angle of yaw. The study of such a cross-flow about a yawed cylinder based on the ideal potential velocity distribution was made by Cooke (1950). Recently, Sarma and Singh (1974) have determined the effects of a cross-flow in the three-dimensional incompressible boundary layer when the chordwise and the spanwise velocity components of the main-stream are perturbed such that the yaw of the wedge is the same in both perturbed and unperturbed flows.

The aim of this paper is to study the variation of the local heat transfer from the wedge at rest (in unsteady flow) with the yaw of the wedge. It is assumed that the temperature of the main-stream is constant. The two cases referred in the abstract are analysed in detail. The perturbations are, in general, supposed to be arbitrary functions of time.

The equations are linearized as by Lighthill (1954) and two different solutions, one for large times and the other for small times are obained. The joining of the two solutions is illustrated graphically by giving particular values to the parameters occurring in the analysis. From the graph it is clear that the local heat transfer increases with the yaw of the wedge as it does with time.

The analysis is kept fairly general to include many problems by introducing arbitrary constants and functions wherever possible.

2. Basic equations

Assuming the flow to be independent of the spanwise direction, the boundary layer equation of enegry for three-dimensional incompressible flow past an infinite yawed wedge is

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + w\frac{\partial T}{\partial z} = \frac{\nu}{\sigma}\frac{\partial^2 T}{\partial z^2} + \frac{\nu}{C_p}\left\{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right\} \qquad \ldots(1)$$

where x is the distance measured along the chordwise direction from the stagnation point and z is the distance perpendicular to the wall; u and w the velocity components in x and z directions respectively, v being that along the spanwise direction; T the temperature; t the time, C_p the specific heat at constant pressure; ν the coefficient of kinematic viscosity; and σ the Prandtl number. Let the temperature T_M of the main-stream be a constant, the temperature difference $(T - T_M)$ between the wall and the main-stream in steady state be a power law $a_1x^{m_1}$(a_1 and m_1 being constants) and the perturbation in the steady wall temperature be $\epsilon a_2x^{m}2T_b(t)$ (a_2 and m_2 are constants, $T_b(t)$ an arbitrary function of time, ϵ being a small reference parameter). This means, the boundary conditions are

$$\left.\begin{aligned} &T - T_M = a_1x^{m_1} + \epsilon a_2x^{m_2}T_b(t) \text{ at } z = 0 \\ &\text{and} \\ &T \to T_M \text{ as } z \to \infty. \end{aligned}\right\} \qquad \ldots(2)$$

To solve eqn. (1), assuming that the unsteady flow is a perturbed one about a steady mean and following the work of Lighthill (1954), we write

$$\left.\begin{aligned} T &= T_0(x, z) + \epsilon T_1(x, z, t) \\ u &= u_0(x, z) + \epsilon u_1(x, z, t) \\ v &= v_0(x, z) + \epsilon v_1(x, z, t) \\ w &= w_0(x, z) + \epsilon w_1(x, z, t). \end{aligned}\right\} \qquad \ldots(3)$$

The '0' and '1' suffixed quantities denote the steady and the unsteady parts respectively. Substituting (3) in eqn. (1) and neglecting ϵ^2 terms, we get the following equations for T_0 and T_1.

$$u_0\frac{\partial T_0}{\partial x} + w_0\frac{\partial T_0}{\partial z} = \frac{\nu}{\sigma}\frac{\partial^2 T_0}{\partial z^2} + \frac{\nu}{C_p}\left\{\left(\frac{\partial u_0}{\partial z}\right)^2 + \left(\frac{\partial v_0}{\partial z}\right)^2\right\} \qquad \ldots(4)$$

with

$$T_0 - T_M = a_1x^{m_1} \text{ at } z = 0 \text{ and } T_0 \to T_M \text{ as } z \to \infty$$

for steady state and

$$\frac{\partial T_1}{\partial t} + u_0 \frac{\partial T_1}{\partial x} + u_1 \frac{\partial T_0}{\partial x} + w_0 \frac{\partial T_1}{\partial z} + w_1 \frac{\partial T_0}{\partial z}$$

$$= \frac{\nu}{\sigma} \frac{\partial^2 T_1}{\partial z^2} + \frac{2\nu}{C_p} \left\{ \frac{\partial u_0}{\partial z} \frac{\partial u_1}{\partial z} + \frac{\partial v_0}{\partial z} \frac{\partial v_1}{\partial z} \right\} \quad \ldots(5)$$

with

$$T_1 = a_2 x^{m_2} T_b(t) \text{ at } z = 0 \text{ and } T_1 \to 0 \text{ as } z \to \infty$$

for unsteady part. In the following paragraphs we shall find the solutions of eqns. (4) and (5).

3. Solution of Steady Equation

If the main-stream is given by

$$\left. \begin{aligned} U &= a x^m \{1 + \epsilon x^\alpha U_M(t)\} \\ V &= a\beta \{1 + \epsilon x^\alpha U_M(t)\} \end{aligned} \right\} \quad \ldots(6)$$

to solve equation (4), we assume :

$$\left. \begin{aligned} T_0 - T_M &= a_1 x^{m_1} \theta_1(\eta) + \frac{a^2}{C_p} \{x^{2m} \theta_2(\eta) + \beta^2 \theta_3(\eta)\} \\ \eta &= \left\{ \frac{\alpha x^{m-1}}{\nu} \right\}^{1/2} P z, \; P^2 = \frac{m+1}{2} \end{aligned} \right\} \quad \ldots(7)$$

where the constants α, β and a signify the angle of perturbation of the velocity vector, the yaw of the wedge and the magnitude of velocity in steady state respectively; and θ_1, θ_2 and θ_3 are arbitrary functions of η and satisfy the differential eqns. (8), (9) and (10) respectively. Substituting (7) in (4) along with the values of u_0, v_0 and w_0 from Sarma and Singh (1971) and equating the coefficients of various powers of x we get

$$\frac{2m_1}{m+1} f' \theta_1 - f \theta_1' = \frac{1}{\sigma} \theta_1'', \quad \ldots(8)$$

with

$$\theta_1(0) = 1, \; \theta_1(\infty) = 0,$$

$$\frac{4m}{m+1} f' \theta_2 - f \theta_2' - f''^2 = \frac{1}{\sigma} \theta_2'', \quad \ldots(9)$$

with

$$\theta_2(0) = \theta_2(\infty) = 0,$$

$$f \theta_3' + g'^2 = -\frac{1}{\sigma} \theta_3'', \quad \ldots(10)$$

with

$$\theta_3(0) = \theta_3(\infty) = 0,$$

where f and g satisfy the equations given by Sarma (1964) and Rosenhead (1963) respectively. Thus the partial differential equation (4) is reduced to a set of three ordinary differential equations containing the constants m, m_1 and σ. This set constitutes a system of equations linear in η. It is a two-point boundary value problem, so it is first converted into an initial value problem and then the equations are solved numerically on I.B.M. 1620 Computer using the Runge-Kutta method and the results are given in Table I. The amount of the local heat transfer $-K_1\left(\frac{\partial T_0}{\partial z}\right)_{z=0}$ from the wall to the fluid, in dimensionless form, is given by

$$q_0 = \frac{1}{a_1}\left(\frac{\partial T_0}{\partial z}\right)_{z=0}\left\{\frac{\nu}{ax^{2m_1+m-1}}\right\}^{1/2}$$

$$= P\{\theta_1'(0) + E\theta_2'(0) + E\beta_1^2\theta_3'(0)\} \qquad \ldots(11)$$

where

$$E\,(\text{Eckert number}) = \frac{U_0^2}{C_p a_1 x^{m_1}},\ \beta_1 = \frac{\beta}{x^m},\ U_0 = ax^m \qquad \ldots(12)$$

K_1 = the coefficient of thermal conductivity. Thus having calculated the local heat transfer in steady state, we shall analyse the problem of unsteady flow.

4. Unsteady Part for Large Times

To solve (5) for large times, just as in Sarma (1965), we assume that

$$T_1(x, \eta, t) = a_1 \sum_{n=0}^{\infty} a^{-n} x^{(1-m)n+m_1+\alpha}\, T_{1,n}(\eta)\, \frac{d^nU_M}{dt^n}$$

$$+ \frac{a^2}{C_p} \sum_{n=0}^{\infty} a^{-n} x^{(1-m)n+\alpha}\, \{x^{2m}T_{2,n}(\eta) + \beta^2 T_{3,n}(\eta)\}\, \frac{d^nU_M}{dt^n}$$

$$+ a_2 \sum_{n=0}^{\infty} a^{-n} x^{(1-m)n+m_2}\, T_{4,n}(\eta)\, \frac{d^nT_b}{dt^n}. \qquad \ldots(13)$$

Substituting (13) and (7) along with the values of u_0, u_1 etc. from Sarma and Singh (1971) in (5) and equating the coefficients of $\frac{d^nU_M}{dt^n}$ and $\frac{d^nT_b}{dt^n}$, we get the following equations :

$$\frac{P^2}{\sigma} T''_{1,n} + P^2 f T'_{1,n} - (n - nm + m_1 + \alpha) f' T_{1,n}$$
$$= T_{1,n-1} + m_1 \theta_1 \phi'_n - \frac{1}{2}(2n - 2nm + m + 2\alpha + 1)\theta'_1 \phi_n \quad \text{...(14)}$$

$$\frac{P^2}{\sigma} T''_{2,n} + P^2 f T'_{2,n} - (n - nm + 2m + \alpha) f' T_{2,n}$$
$$= T_{2,n-1} + 2m\theta_2 \phi'_n - \frac{1}{2}(2n - 2nm + m + 2\alpha + 1)\theta'_2 \phi_n - (m+1) f'' \phi''_n \quad \text{...(15)}$$

$$\frac{P^2}{\sigma} T''_{3,n} + P^2 f T'_{3,n} - (n - nm + \alpha) f' T_{3,n}$$
$$= T_{3,n-1} - \frac{1}{2}(2n - 2nm + m + 2\alpha + 1)\theta'_3 \phi_n - (m+1) g' h'_n \quad \text{...(16)}$$

$$\frac{P^2}{\sigma} T''_{4,n} + P^2 f T'_{4,n} - (n - nm + m_2) f' T_{4,n} = T_{4,n-1} \quad \text{...(17)}$$

with

$$\left.\begin{array}{l} T_{r,n}(0) = T_{r,n}(\infty) = 0 \text{ for } n \geqslant 0,\ r = 1, 2, 3 \\ T_{4,0}(0) = 1,\ T_{4,n}(0) = 0 \text{ for } n \geqslant 1 \text{ and } T_{4,n}(\infty) = 0 \text{ for } n \geqslant 0 \end{array}\right\} \quad \text{...(18)}$$

where the terms with negative subscripts are assumed to be zero. Thus the partial differential equation (5) is reduced to a set of four ordinary differential equations containing the constants m, m_1, m_2, σ and α. This set constitutes a system of linear equations with η as an independent variable. It is a two-point boundary value problem, so it is first converted into an initial value problem and then the equations are solved numerically on I.B.M. 1620 computer using the Runge-Kutta method and the results are given in Table II. The amount of unsteady part of the local heat transfer $-K_1\left(\frac{\partial T_1}{\partial z}\right)_{z=0}$ is given by

$$q_1 = \frac{1}{a_1 U_M}\left(\frac{\partial T_1}{\partial z}\right)_{z=0}\left\{\frac{\nu}{a x^{2m_1+2\alpha+m-1}}\right\}^{1/2}$$
$$= P\left[\sum_{n=0}^{\infty}\left(\frac{x^{1-m}}{a}\right)^n \frac{1}{U_M}\frac{d^n U_M}{dt^n} T'_{1,n}(0)\right.$$
$$\left. + E\sum_{n=0}^{\infty}\left(\frac{x^{1-m}}{a}\right)^n \frac{1}{U_M}\frac{d^n U_M}{dt^n}\{T'_{2,n}(0) + \beta_1^2 T'_{3,n}(0)\}\right]$$
$$+ AP\sum_{n=0}^{\infty}\left(\frac{x^{1-m}}{a}\right)^n \frac{1}{T_b(t)}\frac{d^n T_b(t)}{dt^n} T'_{4,n}(0). \quad \text{...(19)}$$

Thus we see that the unsteady part of the local heat transfer depends on :

$$E,\ \beta_1 \text{ and } A\left(=\frac{a_2 T_b x^{m_2-m_1-\alpha}}{a_1 U_M}\right)$$

the dimensionless variables.

(i) In case when the chordwise and the spanwise velocity components of the main-stream are increased impulsively by $\epsilon a x^{m+\alpha}$ and $a\beta x^{\alpha}$ respectively and the temperature of the wall is steady, the dimensionless local heat transfer (19) becomes :

$$q_1 = P\{T'_{1,0}(0) + E(T'_{2,0}(0) + \beta_1^2 T'_{3,0}(0))\}. \qquad ...(20)$$

(ii) If, in the above case the temperature of the wall is also increased impulsively by an amount $\epsilon a_2 x^{m_2}$, then the local heat transfer (19) becomes :

$$q_1 = P\{T'_{1,0}(0) + E(T'_{2,0}(0) + \beta_1^2 T'_{3,0}(0)) + AT'_{4,0}(0)\}. \qquad ...(21)$$

If, the temperature of the wall is increased by an amount $\epsilon a_2 x^{m_2} t$, then (19) becomes :

$$q_1 = P\left\{T'_{1,0}(0) + E\,(T'_{2,0}(0) + \beta_1^2 T'_{3,0}(0)) + A(T'_{4,0}(0) + \frac{1}{N} T'_{4,1}(0))\right\} \qquad ...(22)$$

and

$$N = a x^{m-1} t$$

where N is the dimensionless time variable which represents the ratio of diffusion time to that of convection time. Thus we can study the different cases. The behaviour of these with various parameters are illustrated graphically in Figs. 1 and 2.

5. Unsteady Part for Small Times

Following Sarma (1964), we obtain the solution of (5) for small times. It can be shown that

$$T_1 = \int_0^{t_1} U_M(t_1-\tau)\, T_1^{(1)}(x, \eta_1, \tau)\, d\tau + \int_0^{t_1} T_b(t_1-\tau)\, T_1^{(2)}(x, \eta_1, \tau)\, d\tau \qquad ...(23)$$

where $T_1^{(1)}$ and $T_1^{(2)}$ are Laplace inverses of

$$\left.\begin{aligned} \bar{T}_1^{(1)} &= a_1 \sum_{n=0}^{\infty} \left(\frac{1}{s}\right)^{n/2} x^{1/2(nm-n+2m_1+2\alpha)}\, F_n(E, \beta_1, \eta_1) \\ \bar{T}_1^{(2)} &= a_2 \sum_{n=0}^{\infty} \left(\frac{1}{s}\right)^{n/2} x^{1/2(nm-n+2m_2)}\, G_n(\eta_1) \end{aligned}\right\} \qquad ...(24)$$

and

$$\left.\begin{aligned} F_n(E, \beta_1, \eta_1) &= L_n(\eta_1) + EP_n(\eta_1) + E\beta_1^2\, Q_n(\eta_1) \\ \eta_1 &= \left(\frac{as}{\nu}\right)^{1/2} z,\ t_1 = at. \end{aligned}\right\} \quad \ldots(25)$$

The functions F_n and G_n satisfy the following differential equations :

$$\frac{1}{\sigma}\frac{\partial^2 F_n}{\partial \eta_1^2} - F_n \begin{cases} = 0 \text{ for } n = 0 \\ = -\frac{1}{2}\sum\limits_{r=0}^{n-2} r(m-1)(n-r-2) + 2m + 2\alpha P^r \eta_1^{r-1}\{\theta_{1,r} \\ \qquad + E\theta_{2,r} + E\beta_1^2\,\theta_{3,r}\}\, Y_{n-r-2} \\ \quad + \frac{1}{2}\sum\limits_{r=0}^{n-2} (P\eta_1)^r\,[\{(m-1)r + 2m_1\}\,\theta_{1,r} + \{r(m-1) + 4m\} \\ \qquad E\theta_{2,r} + r(m-1)\,E\beta_1^2\,\theta_{3,r}]\, Y'_{n-r-2} \\ \quad - 2E\sum\limits_{r=0}^{n-1} (r+1)(r+2)\, b_{r+2} P^{r+1}\eta_1^r\, Y''_{n-r-1} \\ \quad - 2E\beta_1^2 \sum\limits_{r=0}^{n-1} (r+1)\, c_{r+1} P^{r+1} \eta_1^r\, H'_{n-r-1} \\ \quad + \frac{1}{2}\sum\limits_{r=0}^{n-3} \{(r+3)(1-m) - 2\}\, b_{r+2} P^{n+1} \eta_1^{r+2} \frac{\partial}{\partial \eta_1} F_{n-r-3} \\ \quad + \sum\limits_{r=0}^{n-3} (r+2)\, b_{r+2} (P\eta_1)^{r+1} \left\{x\frac{\partial}{\partial x} F_{n-r-3} + (\frac{1}{2}(m-1) \right. \\ \qquad \left. \times (n-r-3) + m_1 + \alpha)\, F_{n-r-3}\right\} \end{cases} \quad \ldots(26)$$

for $n \geqslant 1$ and $r \geqslant 0$, with $F_n = 0$ at $\eta_1 = 0$ and $F_n \rightarrow 0$ as $\eta_1 \rightarrow \infty$ for $n \geqslant 0$, and

$$\frac{1}{\sigma} G''_n - G_n \begin{cases} = 0 \text{ for } n = 0, 1, 2, \\ = \frac{1}{2}\sum\limits_{r=0}^{n-3} (r+2)\{(m-1)(n-r-3) + 2m_2\}\, b_{r+2}(P\eta_1)^{r+1} \\ \times G_{n-r-3} - \frac{1}{2}\sum\limits_{r=0}^{n-3} \{(m-1)(r+3) + 2\}\, b_{r+2}\, P^{r+1}\eta_1^{r+2}\, G'_{n-r-3} \end{cases} \quad \ldots(27)$$

for $n \geqslant 3$ and $r \geqslant 0$, with $G_0(0) = 1$, $G_n(0) = 0$ for $n \geqslant 1$ and $G_n(\infty) = 0$ for $n \geqslant 0$. The quantities with negative subscript vanish. The equations satisfied by Y_n and H_n can be obtained from Gupta (1970), and Sarma and Singh (1971), the equations satisfied by L_n, P_n and Q_n can be obtained by substituting (25) in (26) and equating the coefficients of various powers of x. The values of b_n, c_n and $\theta_{r,n}$ are given by

$$f(\eta) = \sum_{n=0}^{\infty} b_{n+2}\, \eta^{n+2},\quad g(\eta) = \sum_{n=0}^{\infty} c_{n+1}\, \eta^{n+1} \qquad \text{...(28)}$$

$$\theta_r(\eta) = \sum_{n=0}^{\infty} \theta_{r,n}\, \eta^n \text{ for } r = 1, 2 \text{ and } 3. \qquad \text{...(29)}$$

Just as in Sarma (1964), general solutions of (26) and (27) satisfying the boundary conditions at the wall can be assumed to be

$$F_n(E, \beta_1, \eta_1) = \sum_{r=0}^{\infty} \eta_1^r\, F_{r,n}^{(1)}(E, \beta_1) + e^{-\eta_1} \sum_{r=0}^{\infty} \eta_1^r\, F_{r,n}^{(2)}(E, \beta_1)$$

$$+ e^{-\sqrt{\sigma}\eta_1} \sum_{r=0}^{\infty} \eta_1^r\, F_{r,n}^{(3)}(E, \beta_1) \qquad \text{...(30)}$$

and

$$G_n(\eta_1) = e^{-\sqrt{\sigma}\eta_1} \sum_{r=0}^{\infty} \eta_1^r\, G_{r,n} \qquad \text{...(31)}$$

where $F_{r,n}^{(i)}(E, \beta_1)$ ($i = 1, 2$ and 3) and $G_{r,n}$ can be obtained by solving the differential equations (26) and (27). The amount of unsteady part of the local heat transfer $-K_1\left(\frac{\partial T_1}{\partial z}\right)_{z=0}$ is given below in different cases.

(i) In case when the chordwise and the spanwise velocity components of the main-stream are increased impulsively by $\epsilon a x^{m+\alpha}$ and $a\beta x^{\alpha}$ respectively and the temperature of the wall is steady.

$$q_1 = \frac{1}{a_1 U_M}\left\{\frac{\nu}{a x^{2m_1+2\alpha+m-1}}\right\}^{1/2}\left(\frac{\partial T_1}{\partial z}\right)_{z=0}$$

$$= \frac{2\sigma P(1-\sqrt{\sigma})}{1-\sigma} E\{f''(0) + \beta_1^2 g'(0)\} + \frac{2\sigma(\sqrt{\sigma}-1)}{\sqrt{\pi}} N^{1/2}\left\{\frac{m_1}{1-\sigma}\right.$$

$$\left. + \frac{8P^2E}{(1-\sigma)^2}\left(\frac{m}{m+1}\right)\right\} + 2\left(\frac{\sigma N}{\pi}\right)^{1/2}\left\{m_1 + \frac{4\sqrt{\sigma}EP^2}{1-\sigma}\left(\frac{m}{m+1}\right)\right\} +$$

(*equation continued on p.* 743)

$$+\frac{\sigma(1-\sqrt{\sigma})\,PN}{1-\sigma}\Big[2E\{(2m+\alpha)\,f''(0)+\alpha\beta_1^2\,g'(0)\}+(m+\alpha)\{\theta_1'(0)$$

$$+E(\theta_2'(0)+\beta_1^2\,\theta_3'(0))\}+\frac{1}{1-\sigma}\{(m+2m_1-1)\,\theta_1'(0)+E((5m-1)\,\theta_2'(0)$$

$$+(m-1)\,\beta_1^2\,\theta_3'(0))\}\Big]+P(1-\sqrt{\sigma})(m+\alpha)\,N\{\theta_1'(0)+E(\theta_2'(0)+\beta_1^2\theta_3'(0))\}$$

$$-\frac{PN}{2(1-\sigma)}\{(m+2m_1-1)\,\theta_1'(0)+E((5m-1)\,\theta_2'(0)+(m-1)\,\beta_1^2\,\theta_3'(0))\}$$

$$=Q\ (\text{say}). \qquad \ldots(32)$$

(ii) If, in the above case the temperature of the wall is also increased impulsively by an amount $\epsilon a_2 x^{m_2}$, then

$$q_1=Q+A\left\{-\left(\frac{\sigma}{N\pi}\right)^{1/2}+\frac{P}{16}(1-3m-4m_2)\,Nf''(0)\right\}. \qquad \ldots(33)$$

If, the temperature of the wall is increased by an amount $\epsilon a_2 x^{m_2} t$, then

$$q_1=Q+A\left\{-2\left(\frac{\sigma}{N\pi}\right)^{1/2}+\frac{P}{32}(1-3m-4m_2)\,Nf''(0)\right\}. \qquad \ldots(34)$$

The behaviour of these with various parameters are illustrated graphically in Figs. 1 and 2.

6. Conclusion

From the Figs. 1 and 2 we find that the unsteady part of the local heat transfer increases with the yaw of the wedge and it also increases for small times and shows a tendency of joining with that for large times. In the case when the velocity field is perturbed and the temperature is steady the solutions for small and large times agree at $N = 0.10,\ 0.22,\ 0.33$ approximately for $\beta_1 = 1.0, 1.5, 2.0$ respectively. That is, the small time solutions can be taken to be true up to the values $N = 0.10, 0.22, 0.33$, approximately for $\beta_1 = 1.0,\ 1.5,\ 2.0$ respectively. That is, the small time solutions can be taken to be true up to the values $N = 0.10, 0.22, 0.33$ approximately for different values of β_1 and thereafter the large time solutions dominate. In addition, if the steady temperature is also increased by $\epsilon a_2 x^{m_2}$ then the solutions agree at $N = 0.19$, 0.30, 0.34 approximately for $\beta_1 = 1.0, 1.5, 2.0$ respectively. That is, the small time solutions can be taken to be true up to the values $N = 0.19, 0.30,\ 0.34$ approximately for different values of β_1 and there after large time solutions dominate. These facts are clear from Fig. 1.

Instead, if the steady temperature is increased impulsively by $\epsilon a_2 x^{m_2} t$ then the solutions show the tendency of joining, rather than a smooth joining, due to slow convergence of the series solutions. It may be made to join if we take higher order terms in the series. This is clear from Fig. 2.

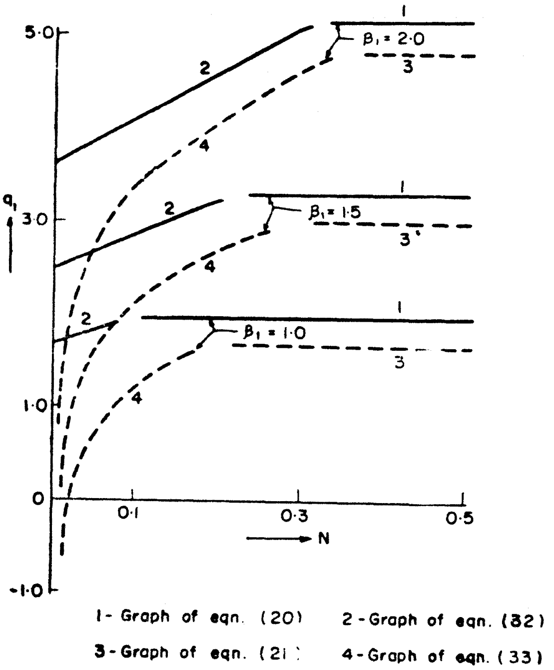

FIG. 1. Variation of local heat transfer with the dimensionless time variable N ($E = 2.0$, $A = 0.5$).

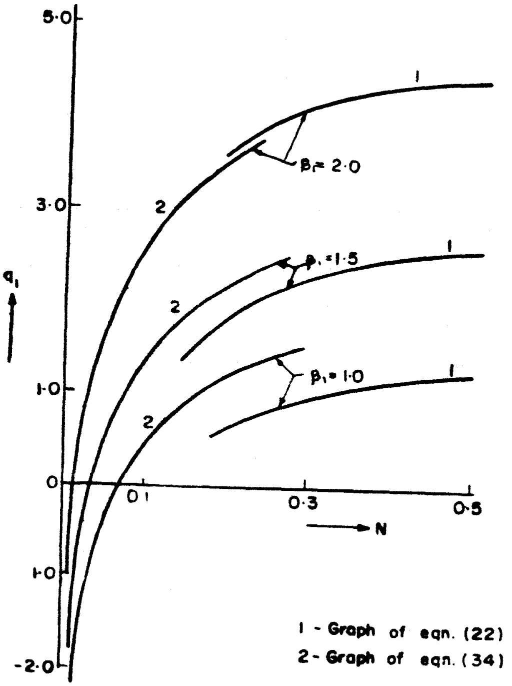

FIG. 2. Variation of local heat transfer with the dimensionless time variable N ($E = 2.0$, $A = 0.5$).

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APPENDIX

Here we shall give the numerical values of the functions used.

TABLE I ($m_1 = 1$)

m	$\theta_1'(0)$	$\theta_2'(0)$	$\theta_3'(0)$	$f''(0)$	$g'(0)$
0.25	−0.7354	0.2604	0.1954	0.8544	0.5300

TABLE II ($m_1 = m_2 = 1$)

m	α	$T'_{1,0}(0)$	$T'_{2,0}(0)$	$T'_{3,0}(0)$	$T'_{4,0}(0)$	$T'_{4,1}(0)$	$h'_0(0)$	$h'_1(0)$	$\phi''_0(0)$	$\phi''_1(0)$
0.25	0.75	−0.5983	0.8701	0.6697	−0.7354	−0.5560	1.8694	0.2434	2.1740	0.2667