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EQUILIBRIUM TEMPERATURES OF MASS TRANSFER COOLED WALLS IN HIGH-SPEED FLOW OF AN ABSORBING-EMITTING GAS

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ABSTRACT

The Couette flow model was used to study radiation interaction effects in high-speed flow with mass transfer cooling. The particular case studied in detail corresponds to the equilibrium or recovery wall temperature condition wherein the convection to the wall is balanced by the net radiation away from the wall. The recovery temperature and corresponding temperature profiles are determined for a wide range of the radiation interaction parameter, the mass transfer rate, and the optical thickness for representative values of the Eckert and Prandtl numbers. The results from the optically thin and thick approximations are also compared to those obtained from the more exact analysis.

The relatively simple approach of superposition (i.e., adding the heat transfer for the pure radiation case to that for the pure convection case) is examined. It is shown that this procedure not only predicts the equilibrium wall temperature with reasonable accuracy but also predicts the total heat transfer under conditions where the wall is at a temperature differing from the recovery condition.

Author

INTRODUCTION

The problem of protecting the surfaces of high-speed vehicles from frictional heating has received considerable attention in the last decade. Mass transfer cooling as a means to reduce surface heating has been studied by many investigators. A review of some of the earlier analytical work on laminar boundary layers is given in reference (1). Heat transfer in media capable of emitting, absorbing and scattering radiation has also received a great deal of attention. Besides formulating specific examples, references (2), (3) and (4) present excellent reviews of previous work in the field of radiation energy transport. To date, the interaction of radiation with the other modes of heat transfer in mass transfer cooling situations, or alternately, the influence of mass transfer in problems dealing with radiation interaction has not been examined in great detail. However, as demonstrated in references (5) and (6), the coupling of the two processes can be of definite importance in high-speed flight.

This report presents a study of the temperature distribution under recovery conditions[1] in high-speed laminar Couette flow of an absorbing-emitting gas with surface mass transfer. The governing conservation equations are simplified by the assumption that the properties of the main stream and the coolant are identical and constant. Not only is it assumed that the properties are

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[1]The equilibrium wall temperature (recovery temperature) is defined as the temperature of the wall when the convection to the wall is balanced by the net radiation away from the wall. This definition differs from the normal recovery condition without radiation wherein the temperature gradient at the wall is zero.

independent of temperature but also that the absorption coefficient is independent of wavelength. The influence of mass transfer rate and radiation interaction on the equilibrium wall temperature is studied for values of the optical thickness ranging from optically thin to optically thick gas layers. The radiation interaction parameter which governs the relative role of radiation is varied from pure radiation to pure convection. Numerical results are presented for black walls and for representative values of the Eckert and Prandtl numbers. Since the Couette flow model used here still retains many of the essential features of the related boundary-layer problem, it is expected that the present results will serve as a guide to predict radiation-interaction effects in the more realistic situation.

Due to the complexity of problems involving the interaction of radiation with conduction and convection, it would be advantageous to have a simplified technique to predict surface heat transfer. The method of superposition proposed by Einstein (7) is a possible technique. This method assumes that the total heat transfer at a surface can be obtained from the sum of the pure radiation and pure conduction at the surface neglecting the interaction of the radiation with the other modes of heat transfer. The method has proven to be successful in predicting the total heat transfer in an absorbing-emitting medium between infinite parallel plates with black surfaces (2). Recovery temperatures obtained from the principle of superposition are compared to the more exact results presented in this report. In addition, the total heat transfer results presented in reference (5) are compared to values predicted by superposition.

THEORY

Governing Equations The Couette flow model with its boundary layer counterpart is illustrated in Figure 1. It is assumed that the flow is steady and laminar with viscous dissipation. The walls of the one-dimensional Couette model are black and the absorbing-emitting medium is a non-scattering diffuse gas with an index of refraction of one. It is further assumed that the physical properties of the main stream gas and the injected gas are identical and constant; the absorption coefficient is taken to be independent of temperature, concentration and wavelength.

The energy transport processes are governed by the energy conservation principle which for the present situation[2] can be expressed as

$$\frac{d^2\theta}{d\tau^2} = \frac{RePr}{\tau_o}\frac{d\theta}{d\tau} - \frac{Re^2Pr\,E}{\tau_o^2(e^{Re}-1)^2}\,e^{2Re\,\tau/\tau_o} + \frac{1}{4N}\frac{d}{d\tau}\left(\frac{q_r}{\sigma T_s^4}\right) \qquad (1)$$

where q_r is the radiative heat flux in the y-direction. Taking into account the previous assumptions, the radiative heat flux can be expressed as (2)

$$\frac{q_r}{\sigma T_s^4} = \left\langle 2\left|\theta_W^4 E_3(\tau) - E_3(\tau_o-\tau) + \int_o^{\tau}\theta^4(t)E_2(\tau-t)dt - \int_{\tau}^{\tau_o}\theta^4(t)E_2(t-\tau)dt\right|\right\rangle \qquad (2)$$

[2]The derivation of equation (1) is given in reference (5). The parameters θ and N are based on T_s whereas in reference (5) they are based on T_W. Here, the Eckert number is equal to $u_s^2/c_{pi}T_s$.

where θ_w is the dimensionless wall temperature at $\tau = 0$. Differentiating this expression with respect τ, one obtains

$$\frac{d}{d\tau}\left(\frac{q_r}{\sigma T_s^4}\right) = -2\left\{\theta_w^4 E_2(\tau) + E_2(\tau_o-\tau) + \int_o^{\tau_o} \theta^4(t)E_1(|\tau-t|)dt - 2\theta^4(\tau)\right\} \quad (3)$$

Equations (1) and (3) coupled with a boundary condition at each wall describes the energy transport process. The imposed boundary conditions are $\theta = 1.0$ at $\tau = \tau_o$ and $q = 0$ at $\tau = 0$ where q is the sum of the radiative and convective heat fluxes. This latter condition is given by

$$4N \left.\frac{d\theta}{d\tau}\right|_w = \theta_w^4 - 2E_3(\tau_o) - 2\int_o^{\tau_o} \theta^4(t)E_2(t)dt \quad (4)$$

The first term in equation (4) is the dimensionless convective heat flux $q_c/\sigma T_s^4$ to the wall and the remaining terms represent the net radiative heat flux $q_r/\sigma T_s^4$ away from the wall. In light of equation (4), the dimensionless temperature θ_w appearing in equations (2), (3) and (4) is the equilibrium temperature of the wall.

It is convenient to transform equations (1) and (3) into an integral equation by integrating twice with respect to τ from o to τ. Utilizing the conditions, $\theta = 1$ at $\tau = \tau_o$ and $\theta = \theta_w$ at $\tau = 0$, this integration yields

$$\theta = \theta_w + \frac{\tau}{\tau_o}(1-\theta_w) + \frac{1}{2N}\left\{\theta_w^4 \left[\frac{\tau}{\tau_o} E_4(\tau_o) - E_4(\tau) + \frac{1}{3}\left(1 - \frac{\tau}{\tau_o}\right)\right]\right.$$

$$\left. + \left[\left(1 - \frac{\tau}{\tau_o}\right)E_4(\tau_o) - E_4(\tau_o-\tau) + \frac{1}{3}\frac{\tau}{\tau_o}\right]\right\} + \frac{Pr\ E}{4(e^{Re}-1)^2}\left[\frac{\tau}{\tau_o}\ e^{2Re}\right. \quad .$$

$$- e^{2Re\,\tau/\tau_o} - \frac{\tau}{\tau_o} + 1] + \frac{PrRe}{\tau_o}\left[\int_o^{\tau}\theta(t)dt - \frac{\tau}{\tau_o}\int_o^{\tau_o}\theta(t)dt\right]$$

$$+ \frac{1}{2N}\int^{\tau_o}\left\langle [E_3(t) - E_3(|\tau-t|)] + \frac{\tau}{\tau_o}[E_3(\tau_o-t) - E_3(t)]\right\rangle \theta^4(t)dt \qquad (5)$$

Using the expression for $\left.\frac{d\theta}{d\tau}\right)_w$ obtained from equation (5), the boundary condition for the equilibrium wall temperature θ_w is given by

$$\theta_w^4 = 1 + \frac{1}{[\frac{2}{3} - 2E_4(\tau_o)]}\left\langle 4N[1 + \theta_w(RePr - 1)] + \frac{Pr\;E\;N}{(e^{Re}-1)^2}[e^{2Re}-2Re-1]\right.$$

$$\left. - 2\int^{\tau_o}\left[2\frac{N\;RePr}{\tau_o}\theta(t) + \theta^4(t)E_3(t) - \theta^4(t)E_3(\tau_o-t)\right]dt\right\rangle \qquad (6)$$

Equations (5) and (6) were solved numerically on an IBM 1620 II digital computer using an iterative scheme. The numerical procedure was repeated until the successive approximations for θ were within 0.0001. To obtain convergence for small values of N it was necessary to augment the normal procedure by weighting each new iteration close to the previous one. The exponential integral functions $E_n(\tau)$ were taken from (8).

<u>Approximate Equations</u> When the optical thickness is very small ($\tau_o << 1$), the expressions given by equations (3) and (4) can be simplified by assuming that each gas element exchanges radiation directly with the bounding walls and no attenuation takes place in the intervening gas layers. Under the negligible self-absorption assumption, equations (3) and (4) take the form (2)

$$\frac{d}{d\tau}\left(\frac{q_r}{\sigma T_s^4}\right) = 4\theta^4(\tau) - 2\theta_w^4 - 2 \qquad (7)$$

$$4N \left.\frac{d\theta}{d\tau}\right)_w = \theta_w^4 + (2\tau_o - 1) - 2 \int_o^{\tau_o} \theta^4(t)dt \qquad (8)$$

Using equations (7) and (8) and the boundary condition $\theta = 1$ at $\tau = \tau_o$, equation (1) was solved numerically by an iterative forward integration procedure. Due to the influence of the integral in equation (8) it became increasingly more difficult to obtain a solution as N was decreased.

When the optical thickness is very large ($\tau_o >> 1$), equations (3) and (4) can again be simplified. Through the use of the diffusion approximation for the radiative heat flux $\frac{q_r}{\sigma T_s^4} = - \frac{4}{3} \frac{d\theta^4}{d\tau}$ equation (1) takes the form

$$\frac{d}{d\tau}\left[\left(1 + \frac{4}{3}\frac{\theta^3}{N}\right)\frac{d\theta}{d\tau}\right] = \frac{RePr}{\tau_o}\frac{d\theta}{d\tau} - \frac{Pr\ E\ Re^2\ e^{2Re\ \tau/\tau_o}}{\tau_o^2(e^{Re}-1)^2} \qquad (9)$$

The boundary conditions now reduce to $\theta = 1$ at $\tau = \tau_o$ and $\left.\frac{d\theta}{d\tau}\right)_w = 0$ at $\tau = 0$. The latter boundary condition is just the recovery condition wherein the total heat flux at the wall $\frac{q_w}{\sigma T_s^4} = - \left(4N + \frac{16}{3}\right)\left.\frac{d\theta}{d\tau}\right)_w$ is set equal to zero.

The solution of equation (9) was obtained numerically by forward integration. In the absence of mass transfer, equation (9) can be integrated exactly to yield a fourth order algebraic equation for θ_w.

values of optical thickness and for selected values of N/τ_o. To simplify the calculations, the thin and thick approximations were used to calculate the results for $\tau_o = 0.1$ and 10.0, respectively. On the basis of the comparisons given in Table 1, it is expected that the approximate analyses will yield accurate estimates of the equilibrium wall temperature. The results for $\tau_o = 1.0$ were obtained from equations (5) and (6).

As the role of radiation increases for a fixed τ_o, Figure 6 shows that mass transfer becomes increasingly less effective as a means to reduce the equilibrium wall temperature. Inspection of Figure 6 also indicates that except in the case of pure radiation, $N/\tau_o = 0$, the equilibrium wall temperature decreases with an increase in mass transfer rate. The laminar boundary layer without radiation shows the same trend for Prandtl numbers less than one. It was pointed out in (5) that the mass transfer rate has little influence on the radiative heat flux except in the case of $\tau_o = 10.0$. Thus in the $\tau_o = 0.1$ and 1.0 cases where the radiation and the convection are not highly coupled, the reduction of the equilibrium wall temperature with an increase in blowing is due mainly to the decrease in convection. In general the decrease in the equilibrium wall temperature with an increase in blowing rate is most pronounced for $\tau_o = 0.1$. Inspection of Figure 2, 3 and 4 reveals that at fixed values of N/τ_o the dimensionless convective heat transfer $\frac{q_c}{\sigma T_s^4} = -\frac{4N}{\tau_o}\frac{d\theta}{d\frac{\tau}{\tau_o}})_w$ is largest for an optical thickness of 0.1. Since mass transfer is very effective in reducing the convective heat transfer, its influence on the equilibrium wall temperature for this case is not surprising.

For τ_o = 10.0, the radiation and the convection are highly coupled and the energy transport is a diffusive process. Therefore the variation of θ_w with blowing rate is quite similar to that for pure convection. Inspection of Figure 4 also reveals that the temperature profiles for different values of N/τ_o are quite similar in shape to the pure convection case.

Superposition The method of superposition is a simplified technique for the calculation of the total heat transfer to surfaces in the presence of radiation interaction. This procedure assumes that the total heat transfer can be calculated from the sum of the radiation and conduction at a surface ignoring the effects of radiation interaction. Reasonable results have been obtained in the past for the Couette flow model without dissipation or mass transfer (2). Here the effects of mass transfer and dissipation are included. The equations which are necessary for the calculations are given in the Appendix.

The equilibrium wall temperatures obtained from superposition are compared in Table 1 to the results of the more exact analysis for one mass transfer rate Re = 2.0. Close inspection of Table 1 reveals that the approximate method gives an excellent prediction of the equilibrium wall temperature for the cases examined. The total heat transfer results given in (5) for wall temperatures differing from the equilibrium wall temperature are compared in Table 2 to the results predicted from superposition. In general the agreement is quite satisfactory considering the simplicity of the approximate analysis. Clearly the agreement is excellent for the smallest value of τ_0 where the radiative and convective transport processes are not highly coupled. This should be expected since in the limit as τ_0 goes to zero the superposition procedure becomes exact. In the other limit as τ_0 goes to infinity, the approximate analysis does not correspond to the exact solution. Since the approximate analysis is also exact at the limiting cases of pure radiation and pure convection, the largest discrepancies occur for intermediate values of N/τ_0.

The results seem to indicate that the method of superposition is a meaningful tool for the estimation of total heat transfer at surfaces in the presence of radiation interaction. However, the method has only been examined under a set of restrictive assumptions. It has been shown in (2), for example, that substantial errors arise through the use of the method to predict the total heat transfer for combined conduction and radiation between infinite parallel plates with grey surfaces. Thus, the method may not be applicable to cases where the surfaces have low emissivities. It must be mentioned that the superposition method is only applicable for the prediction of the total heat transfer. The separate radiative and conductive heat fluxes obtained from approximate analysis differ substantially from the more exact components except in the limiting cases of pure radiation and pure convection.

CONCLUDING REMARKS

The results of the analysis of high-speed Couette flow with radiation interaction suggest that the wall temperature under recovery conditions is only moderately sensitive to the mass transfer rate and the optical thickness of the gas layer. On the other hand, the dimensionless equilibrium wall temperature is strongly dependent on the relative magnitude of the radiation participation. As one would expect, mass transfer becomes more effective as the role of convection increases.

The method of superposition has been examined and found to give results within engineering accuracy for the equilibrium wall temperature and the total heat transfer under conditions differing from the recovery condition. The success observed here lends further support to this simplified approach as a tool for the calculation of the total heat transfer in radiation interaction situations. As pointed out in the text, the method needs further examination in situations involving walls of low emissivities.

ACKNOWLEDGMENTS

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NOMENCLATURE

a = absorption coefficient

c_p = specific heat at constant pressure

e = black-body emissive power, σT^4

E = Eckert number, $u_s^2/c_{pi}T_s$

E_n = exponential integral, $E_n(\tau) = \int_0^1 t^{n-2}e^{-\tau/t}\,dt$

k = thermal conductivity

N = dimensionless radiation interaction parameter, $ka/4\sigma T_s^3$

Pr = Prandtl number, $\mu c_{pi}/k$

q = heat flux rate

Re = blowing Reynolds number or dimensionless mass transfer rate, $\rho v\delta/\mu$

t = dummy variable of integration

T = absolute temperature

u = velocity component in x-direction

v = velocity component in y-direction

x = distance along surface

y = distance perpendicular to surface

δ = plate spacing

θ = dimensionless temperature T/T_s

μ = dynamic viscosity

ρ = density

σ = Stefan-Boltzmann constant

τ = optical distance, ay

τ_o = optical distance, $a\delta$

Subscripts

c = convection

i = injected gas

r = radiation

s = wall at $y = \delta$

w = wall at $y = 0$

$( )_\infty$ = refers to the case of no radiation, $N = \infty$

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APPENDIX

Governing Equations for Superposition The expression for the heat transfer at y = 0 for Couette flow with surface mass transfer and dissipation in the absence of radiation is given by

$$\frac{q_c}{\sigma T_s^4} = \frac{4N\ Re}{\tau_o}\left\{ 2F + \frac{[(\theta_w-1)-F(e^{2Re}-1)]Pr}{(e^{Re\ Pr}-1)} \right\} \tag{10}$$

where

$$F = \frac{E\ Pr}{2(2-Pr)(e^{Re}-1)^2}$$

Equation (10) was obtained from results given in (9). Although equation (10) includes the parameter $\frac{N}{\tau_o}$, this by no means implies that the convective heat transfer depends on radiation interaction; the factor $\frac{N}{\tau_o}$ is independent of the absorption coefficient. The dimensionless temperature θ_w can refer to either the wall temperature under recovery conditions or the wall temperature under non-recovery conditions depending on the situation.

The radiative heat transfer at the wall y = 0 for the case of infinite parallel black plates in the absence of conduction and convection can be expressed as (2)

$$\frac{q_r}{\sigma T_s^4} = (\theta_w^4 - 1) \left\{ 2\ E_3(\tau_o) + 2 \int_o^{\tau_o} \phi(t)\ E_2(t)dt \right\} \tag{11}$$

where $\phi(t) = \frac{T^4(t)-T_w^4}{T_s^4 - T_w^4}$. The expression appearing in the brackets in equation (11) is tabulated in (2) as a function of τ_o.

Equations (10) and (11) represent the separate heat fluxes for pure convection and pure radiation for the Couette flow model studied in this report. According to the method of superposition the total heat transfer at the surface in the presence of radiation interaction is given by

$$\frac{q}{\sigma T_s^4} = \frac{q_c + q_r}{\sigma T_s^4} \tag{12}$$

Equations (10), (11) and (12) were used to calculate the approximate equilibrium wall temperatures appearing in Table 1 and the approximate total heat transfer results given in Table 2. The equilibrium wall temperatures were obtained by setting $q = 0$ in equation (12) and solving the resulting algebraic equation for θ_w.

Table 1

Equilibrium Wall Temperature Results for Re = 2.0, E = 27.4 and Pr = 0.7 where $(\theta_w)_\infty = 9.12$. Numbers in Parenthesis Refer to the Thin ($\tau_o = 0.1$) and Thick ($\tau_o = 10.0$) Analyses. θ_w(approx) refers to Superposition

τ_o	N/τ_o	θ_w		θ_w(approx)
0.1	0	1.00	(1.00)	1.00
	1	2.09		1.98
	10	3.35	(3.36)	3.29
	100	5.27	(5.28)	5.27
	1,000	7.51	(7.51)	7.52
	10,000		(8.81)	8.82
1.0	0	1.00		1.00
	1	2.41		2.21
	10	3.82		3.67
	100	5.80		5.77
	1,000	7.89		7.93
10.0	0	1.00	(1.00)	1.00
	0.01		(1.28)	1.23
	0.10		(2.00)	1.90
	1.00	3.37	(3.31)	3.17
	10.0	5.28	(5.28)	5.10
	100	7.44	(7.43)	7.37
	1,000	8.78	(8.77)	8.77

Table 2

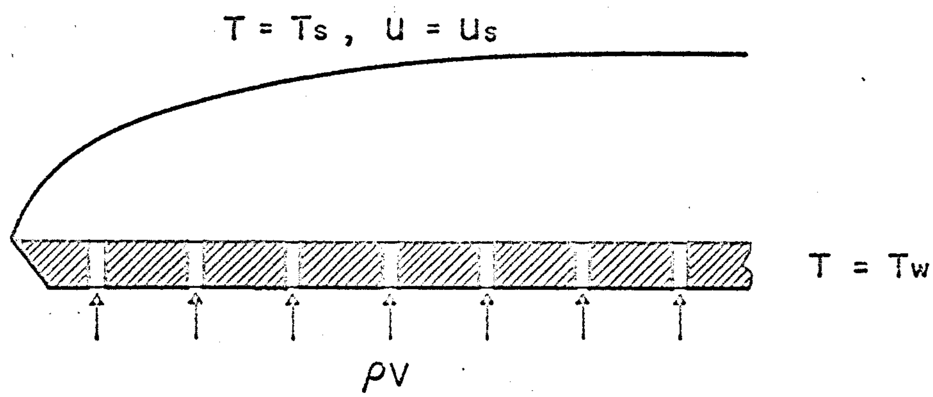
Comparison of the Total Heat Transfer Results Calculated by Superposition to the Non-Recovery Results of (5) for Re = 2.0 and Pr = 0.7.

(a). $\theta(\tau=0) = 4.0$ and $E = 27.4$ where $(q/\sigma T_s^4)_\infty = -9.38\ N/\tau_o$

τ_o	N/τ_o	$q/\sigma T_s^4$,(5)	q(approx)/q
0.1	0	233	1.00
	0.64	228	0.99
	6.4	168	1.03
	64	-381	0.96
	640	-5790	0.99
	6400	-59800	1.00
1.0	0	141	1.00
	0.64	138	0.98
	6.40	68.6	1.18
	64.0	-507	0.91
	640	-5910	0.99
10.0	0	27.6	1.00
	0.64	21.5	1.01
	6.40	-46.1	0.70
	64.0	-607	0.94

(b). $\theta(\tau=0) = 0.25$ and $E = 6.86$ where $(q/\sigma T_s^4)_\infty = -5.10\ N/\tau_o$

τ_o	N/τ_o	$q/\sigma T_s^4$,(5)	q(approx)/q
0.1	0	-0.914	1.00
	0.00156	-0.941	0.98
	0.0156	-1.05	0.95
	0.156	-1.81	0.95
	1.56	-8.99	0.98
1.0	0	-0.551	1.00
	0.00156	-0.582	0.97
	0.0156	-0.719	0.88
	0.156	-1.61	0.84
	1.56	-8.93	0.95
10.0	0	-0.109	1.00
	0.00156	-0.130	0.90
	0.0156	-0.220	0.85
	0.156	-0.992	0.91



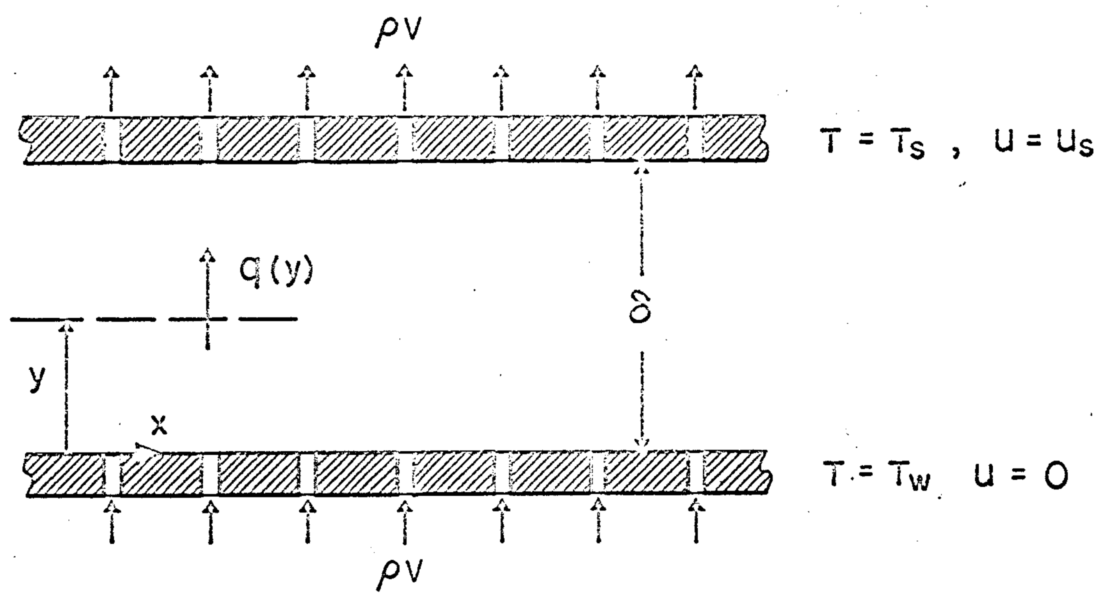


Fig. 1. Schematic of Couette Flow Model and Boundary-Layer Counterpart

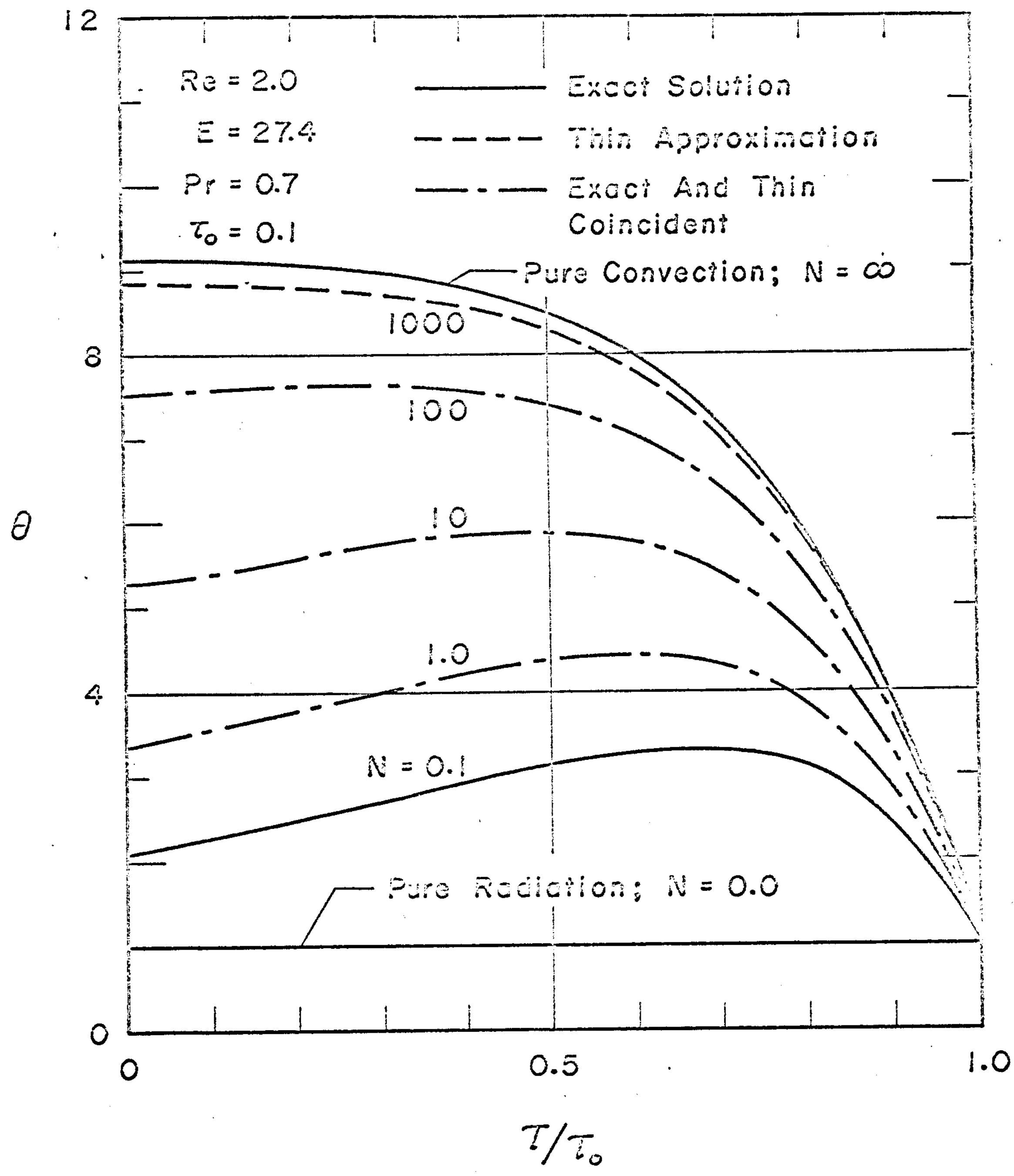


Fig. 2. Effect of Radiation Interaction on the Temperature Distribution Under Recovery Conditions; $\tau_o = 0.1$.

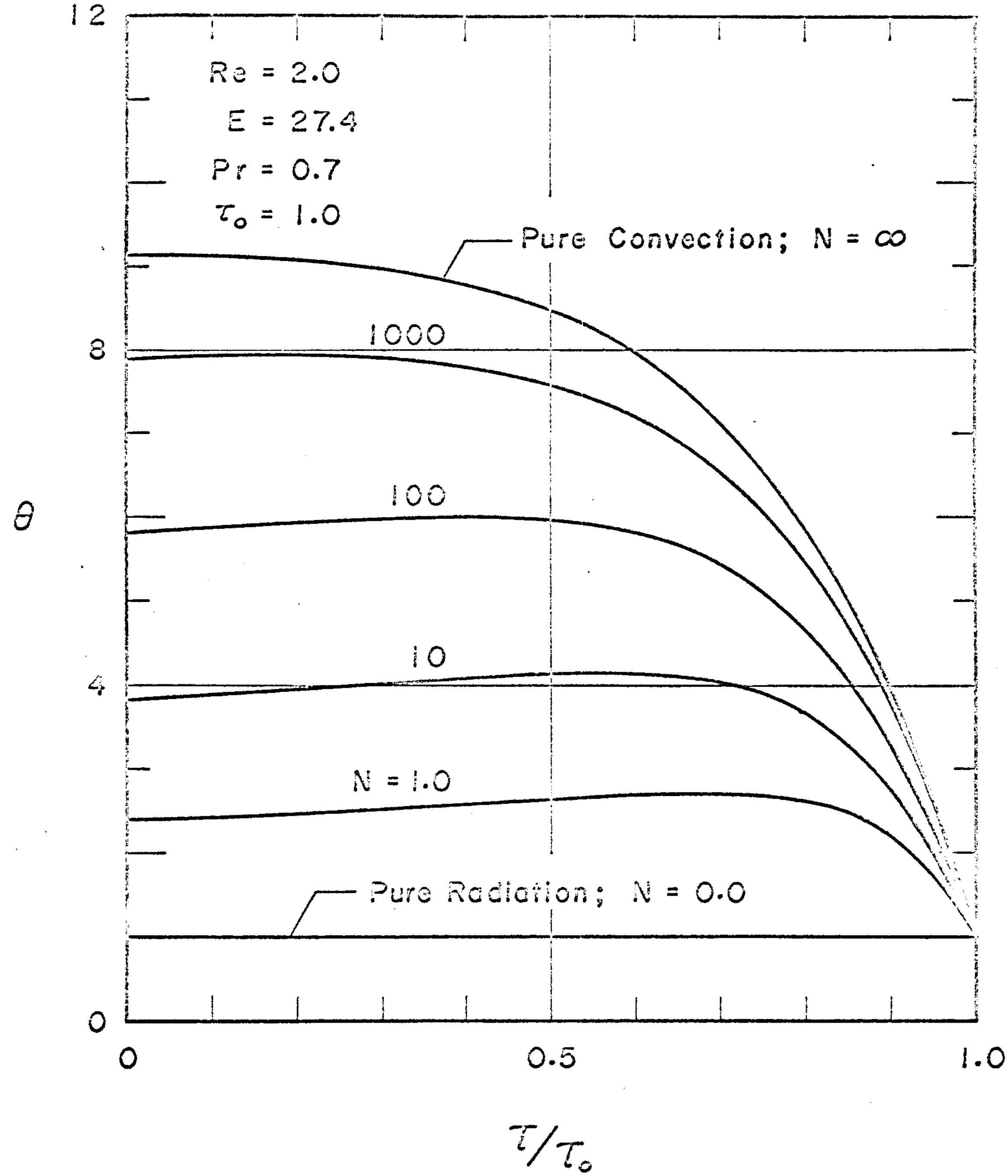


Fig. 3. Effect of Radiation Interaction on the Temperature Distribution Under Recovery Conditions; $\tau_o = 1.0$.

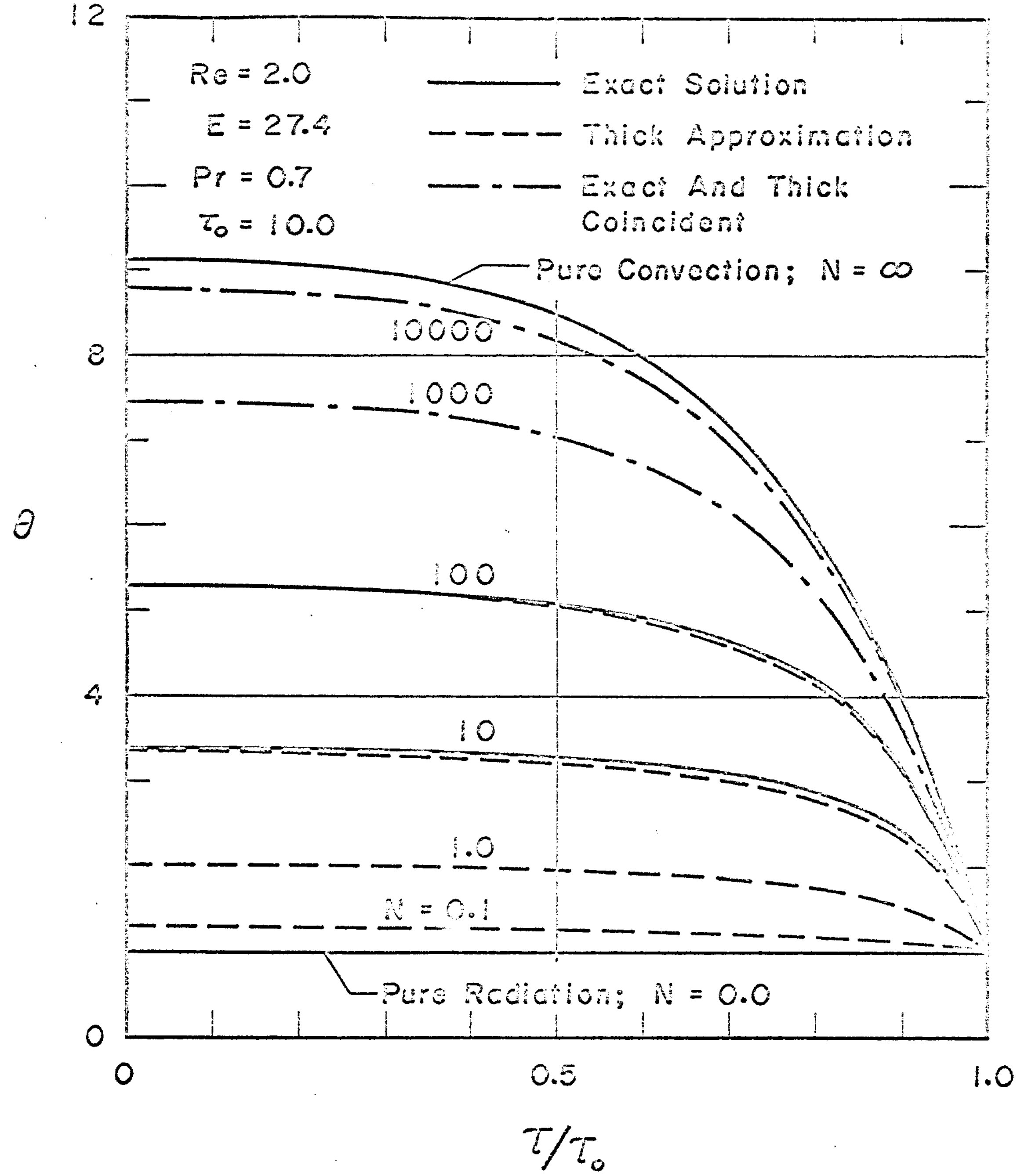


Fig. 4. Effect of Radiation Interaction on the Temperature Distribution Under Recovery Conditions; $\tau_0 = 10.0$.

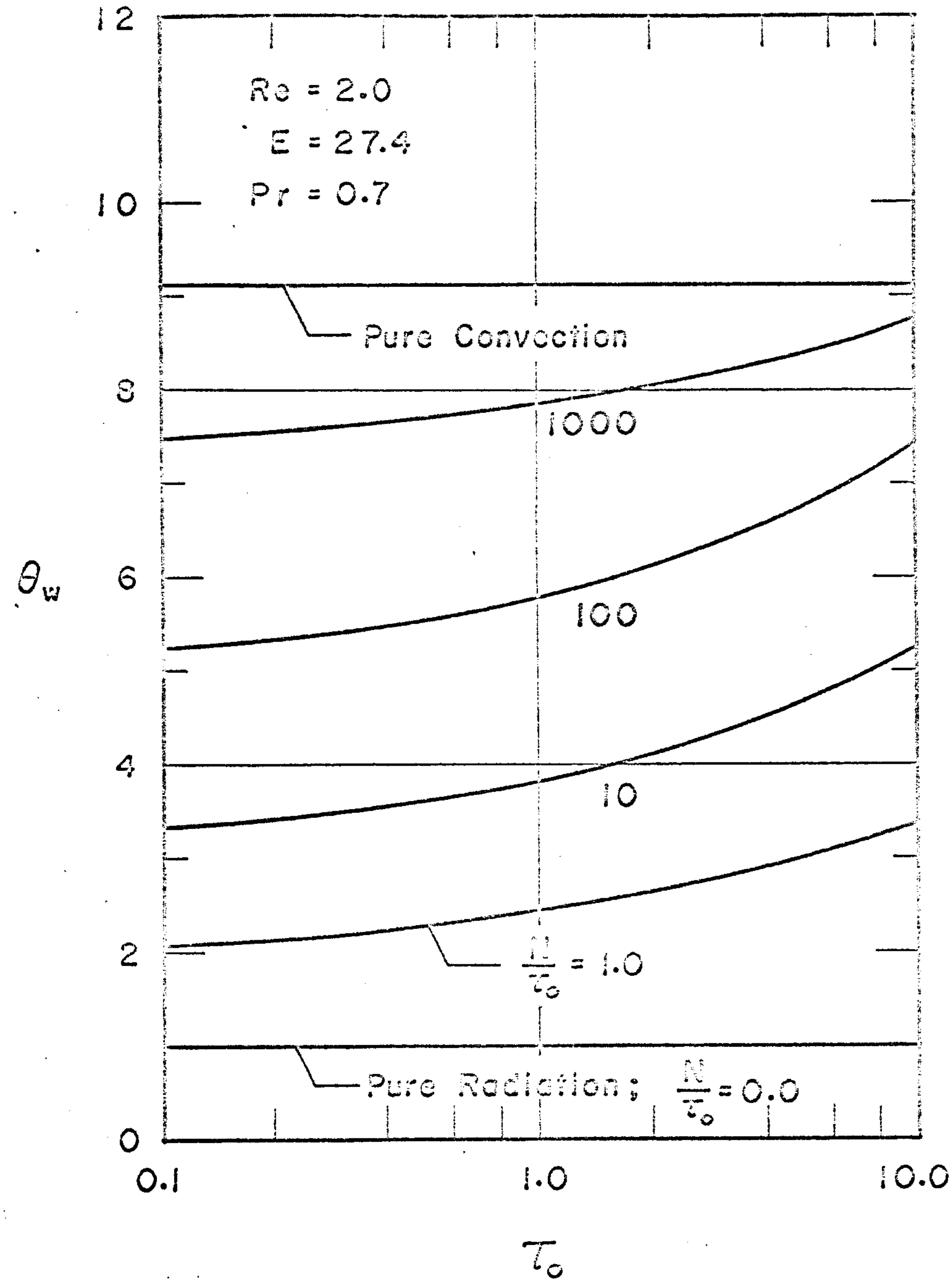


Fig. 5. Effect of the Optical Thickness on the Equilibrium Wall Temperature with N/τ_o as a Parameter

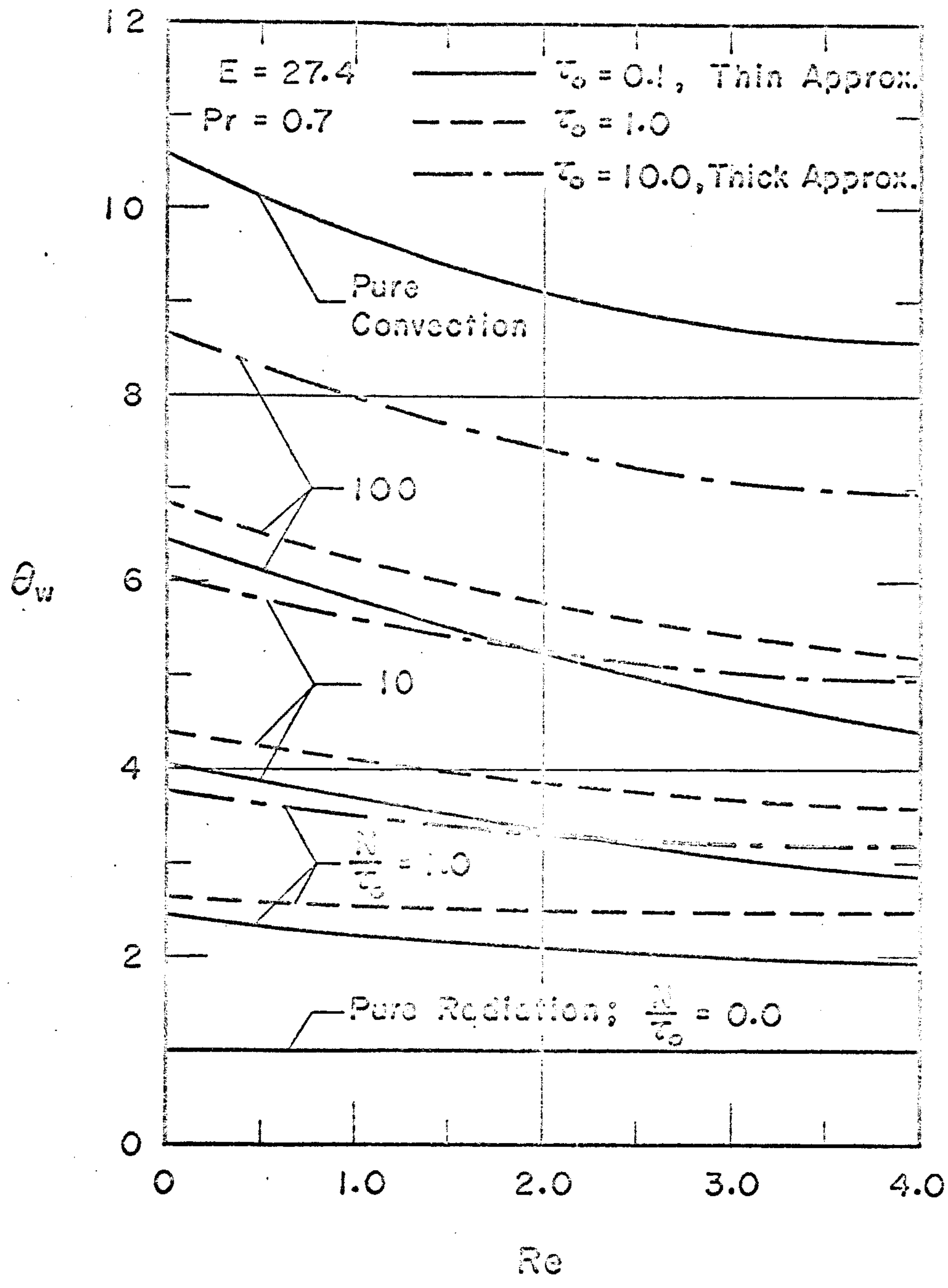


Fig. 6 Effect of Mass Transfer Rate on the Equilibrium Wall Temperature with τ_o and N/τ_o as Parameters