OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

DEPARTMENT OF CHEMICAL SCIENCES
SCHOOL OF SCIENCES AND HEALTH PROFESSIONS
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

ANALYSIS OF AN EFFUSIVE SAMPLING DEVICE FOR ANALYSIS OF BOUNDARY LAYER GASES

By

K. G. Brown, Principal Investigator

Final Report
For the Period December 1, 1982 - September 30, 1983

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Under
Master Contract Agreement NAS-1-17099
Task Authorization No. 8
George M. Wood, Technical Monitor
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The effect of suction, through an opening in a surface, upon a stream of flowing gas is determined. The quantity of interest is the maximum distance, Y, from the surface that the main stream is affected by the applied suction. The fraction of this distance Y of the boundary layer thickness σ is determined as a function of tubing radius and length, gas pressure, temperature and stream velocity. The shape of the flow in the high velocity stream is assumed to be determined by means of a parameter which is an unknown function of the distance from the leading edge of the surface. The parameter is given values up to and including those that have been shown to lead to flow separation(1).

MODEL

The experimental situation is shown in figure 1 where the relevant parameters are also defined. The distance Y represents the streamline which has a velocity u(Y) in the region prior to the suction. This velocity has a zero value at the downstream edge of the suction area. An extensive derivation of the relevant equations will not be shown in this report. The details are given in reference 1. A few of the pertinent equations will be developed as they bear on the proper understanding of the terms in the final working equation.

The starting point is the first order equation for the momentum loss thickness(1).

$$\frac{d\delta_2}{d\chi} + \frac{\delta_2}{u_\delta}\frac{du_\delta}{d\chi}\left[2 + \frac{\delta_1}{\delta_2} - M_\delta^2\right] - \frac{\tau_\omega}{P_\delta u_\delta^2} = 0 \qquad (1)$$

where δ_2 = momentum thickness

δ_1 = displacement thickness

u_δ = freestream velocity

τ_ω = stress at wall

M_δ = mass

P_δ = density

Letting $u = 0$ and $y = 0$ at the downstream edge and assuming mass, momentum and energy are equal to the profile at point 1 and point 2, the following relationships are derived for the quantity of interest, the displacement thickness:

$$(\delta_1)_{II} = (\delta_1)_I - (\delta_1)_q \qquad (2)$$

$$(\delta_{1Q}) = \int_0^Y \left(1 - \frac{u}{u_\delta}\right) dy \qquad (3)$$

where the subscript I stands for the region before suction, II stands for the region after suction and Q represents the suction region. Equation 3 gives a correction to the Y_Q streamline by a ratio of velocities. This correction is called a "suction thickness" as defined in equation 4:

$$\delta Q = \int_0^Y \frac{u}{u\delta} \, dy \qquad (4)$$

The product of the suction thickness and the velocity represents the amount of material that can be removed through the opening per unit area. The amount of material Q is defined in equation 5 as:

$$Q = u_\delta \, \delta q \qquad (5)$$

In order to perform any of the above integrations a functional form for $u/u\delta$ is needed. For the purposes of this study, assuming turbulent boundary layers, the following simplified form is used:

$$\frac{u}{u_\delta} = \left[\frac{y}{\sigma(x)}\right]^{k(x)} \tag{6}$$

where $\sigma(x)$ is the boundary layer thickness. The parameter k is used to define the flow characteristics. A value of k above .7 will be beyond the point of flow separation. It must be emphasized at this point that one of the basic reasons for selecting this functional form is for ease of integration and not because of any rigorous justification from fundamental equations of flow or empirical evidence. Substituting 6 into 4 and integrating we obtain:

$$\delta q = \left(\frac{1}{\sigma}\right) \quad \left(\frac{1}{K + 1}\right) \ Y^{\,k + 1} \tag{7}$$

where $k = k(x)$

Rearranging and solving for Y the following expression is obtained

$$\frac{Y}{\sigma} = \left[(k + 1) \quad \frac{\delta q}{\sigma}\right]^{\frac{1}{k + 1}} \tag{8}$$

Eliminating with equation 5 the working equation is obtained:

$$\frac{Y}{\sigma} = \left[\left(\frac{(k + 1)}{u\delta}\right) \left(\frac{q}{\sigma}\right)\right]^{\frac{1}{k + 1}} \tag{9}$$

This equation relates the maximum distance to parameters that can be readily calculated from other equations as will be shown below. The only parameter that is arbitrarily varied is the shape parameter, k, and that only within the limits described above.

Equation 9 can be generalized by introducing a dimensionless length x/L where L is an arbitrary body length. When this is done a new Reynolds number is defined,

$$Re_L = \frac{\rho u_\delta L}{\eta} \tag{9a}$$

which leads to the definition of a boundary thickness σ_L for the body, and the modified equation 9c.

$$\sigma_L = L/\sqrt{Re_L} \tag{9b}$$

$$Y = \left[(k + 1) \frac{Q}{u\delta} \right]^{\frac{1}{k+1}} \left(\sigma_L\right)^{\frac{k}{k+1}} \left(\frac{X}{L}\right)^{\frac{k}{2(k+1)}} \tag{9c}$$

The log(Y) is shown in figure 2 as a function of the velocity ratio Q/U_δ for various values of σ_L with $x/L = .5$ and $k = .5$.

EVALUATION OF PARAMETERS

1. Flow

Q in equation 9 can be determined using the Poiseuille equation for flow through a finite tube modified for end effects. (ref. 2). This equation is valid for the conditions used in this report where the flow is viscous and laminar.

$$Q = \frac{\pi \alpha^2 (P_2 - P_1)}{8 \eta L \left[1 \times 1.14 \left(\frac{\rho \alpha^2}{8\eta} \right) \frac{Q}{L} \right]} \tag{10}$$

where

P_2 = inlet pressure

P_1 = outlet pressure

a = tube radius

η = viscosity

L = tube length

ρ = density

II. Density

The density ρ is calculated assuming ideal gas behavior.

$$\rho = M.W. (*P/RT) \tag{11}$$

where P = inlet pressure

M.W. = Molecular Weight

R = gas constant

T = Temperature (K)

The assumption of ideal behavior does not present any difficulty since the compressibility factor is very nearly equal to one for most of the gases of concern, in the region of high temperature and low pressure that we are considering.

III. Viscosity

The temperature dependence of the viscosity is determined from an empirical equation proposed by Golubev (ref.3). The viscosity is assumed to be independent of pressure at the low pressures considered here. The Golübev equation is:

$$\begin{aligned} \eta &= \eta_c^* T_r^{.965} \quad Tr < 1 \\ &= \eta_c^* T_r^{(.71 + .29/T_r)} \quad T_r > 1 \end{aligned} \tag{12}$$

$$\frac{M^{\frac{1}{2}} \quad P_c^{\frac{2}{3}}}{T_c^{\frac{1}{6}}}$$

where T_r = reduced Temperature

P_r = reduced pressure

T_c = critical temperature

P_c = critical pressure

The viscosity at high temperature was also calculated, for one set of conditions, using the following relationship proposed by Thodo(3)

$$\eta\xi = 4.610\, T_r^{.618} - 2.04e^{-.449\, T_r} + 1.94e^{-4.058\, T_r} + .1$$

$$\xi = T_c^{1/6}\, M^{-1/2}\, P_c^{-2/3} \tag{13}$$

where the symbols are defined in equation 12. The results of these calculations are shown in table 1 for Nitrogen. The two methods are seen to be in close agreement with one another and with the experimental values. The equation of Golubev was then used in all calculations.

IV. Boundary Layer Thickness

The boundary layer thickness is obtained either from shuttle data (ref.4) or from the following equation:

$$\sigma(x) = x / \sqrt{Re} \tag{14}$$

where x is the distance from the leading edge of the surface and Re is the Reynolds number defined by:

$$Re = \frac{\rho u_\delta x}{\eta} \tag{15}$$

There are other definitions of the boundary layer for other types of flow. These will not be considered here. The expression used here is the one most typically used for flow across a flat plate.

CALCULATIONS

In all of the calculations described in this report the flowing gas was assumed to be NITROGEN. The parameters that can be adjusted are seen to be of two types. In the first group are those variables which affect the suction velocity and the second group consists of those that effect the high velocity stream characteristics. The suction parameters shall be considered first.

A. Suction Parameters

1. Variation of Temperature and Pressure

The effect of temperature on flow velocity is shown in figure 3. The decreasing flow velocity, with increasing temperature is due, primarily, to the increase in viscosity of the gas. At the highest temperatures the variation of the velocity is not as great, attaining a velocity which is relatively insensitive to further temperature changes.

In the tunnel experiment, the temperature of the gas undergoes a rapid rise of 175°C during the experiment. The observed flow approaches a maximum followed by a decrease in flow as the experiment continues. The decrease is partially explained, as discussed above, by the increase in the gas viscosity during the experiment. Taking the temperature of the gas to be at the midpoint of the temperature rise, the calculated time of arrival at the mass spectrometer is 6 seconds, approximately that which is observed.

The effect of pressure and temperature upon the maximum suction length is shown in figure 4. At a given condition of tube radius, length and stream velocity increasing pressure and lowering temperature raises the likelihood that the material removed from the stream will come from outside the boundary layer. The distance Y can be controlled by selecting the appropriate tubing radius and length, as shown below.

2. Effect of Tubing Length and Radius

In figure 5 the effect of tubing radius and length is summarized at one particular condition of streamflow. The larger the radius, or the shorter the tubing, the higher the suction velocity with a resultant increase in the Y/σ ratio. An effective summary of the tubing parameters is given in figure 6 where Y/σ is plotted against a^2/L, a measure of the ratio of a^2 cross-sectional area to tubing length.

B. Effect of Streamflow Characteristics

1. Stream velocity

At high mach flow, the effect of the streamflow velocity upon Y diminishes. For a mach number greater than 2 the ratio Y/σ does not vary appreciably with stream velocity as shown in figure 7.

2. Flow Shape

The flow shape is governed in this model by the parameter k the variation of this parameter and its effect upon the Y/σ is shown in figure 7.

SUMMARY

Wind Tunnel Experiment

For the wind tunnel data, the effect of the cooling Nitrogen upon the boundary layer thickness was ignored. Evaluating equation 8 for the tube length (1800 cm), tube radius (.08 cm) and a Mach of 5 we find the Y/σ = .03, well within the calculated boundary layer. Other characteristics of the flow, delay time and temperature behavior also agree with calculated behavior as discussed in the previous section. This agreement is, quite likely, a consequence of the application of the pouseille equation for tube flow than to any intrinsic validity of the assumptions made about the stream flow.

Shuttle Flight Path

The shuttle data from reference 3 was treated with this model. Using the boundary layer calculated in reference 3 it was found that with a orifice radius of .16 and a tubing length of 10 cm. removal of material from the stream would lie well within the boundary layer calculated in reference 3. As this boundary layer is quite large it would take an extremely high suction velocity to penetrate it. These calculations are not summarized within this report.

Evaluation of the Approximations in the Model

The greatest amount of uncertainty with this approach occurs with the assumption for the velocity ratio made in equation 6. The basic reason for the assumption is the simplification of the calculation. Other velocity profiles are being examined.

The equations used to calculate density and viscosity are approximations. However, at the conditions of temperature and pressure considered here, the error introduced by them is thought to be small.

The boundary layer thickness is a difficult quantity to define or calculate. Other approaches to the calculation do exist and will be tested.

There seems to be no difficulty with the modified poiseuille equation for the flow in the tube, as long as the flow is viscous. Under conditions of extremely low outer pressure the possibility of molecular flow occurs. The equations will then have to be modified.

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3. In "The Properties of Gases and Liquids," 3rd ed., R. C. Reid, J. M. Prausnitz and T. K. Sherwood eds., McGraw-Hill, (1977).

4. Shinn, J. L., Moss, J. N., and Simmonds, A. L. reported at AIAA/ASME 3rd Joint Thermophysics, Fluids Plasma and Heat Transfer Conference (1982).

Table 1. Comparisons of calculated viscosities.

T(K)	Thodos	Golubev	exp
	in	Poise	
1000	407	402	399
900	381	375	375
800	353	346	350
700	324	316	321
600	292	285	289
500	258	252	255
400	221	216	218
300	178	176	178

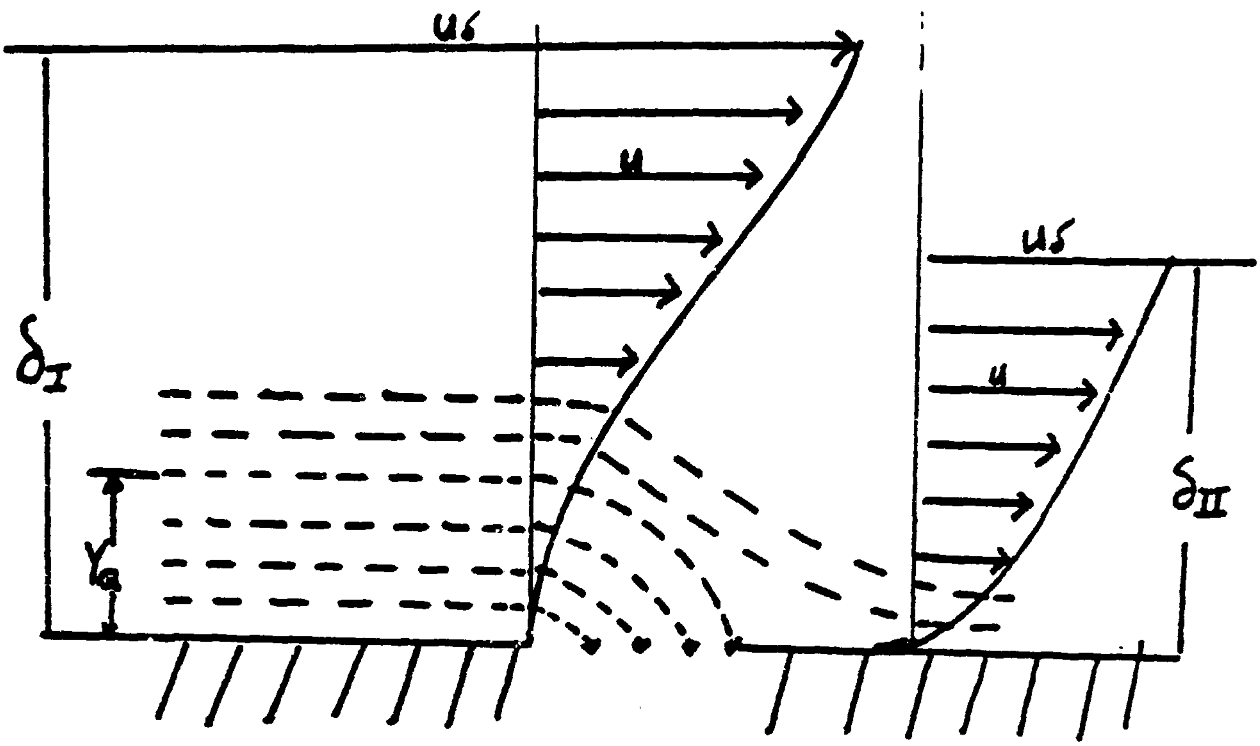

Figure 1. Assumed flow pattern across a flat plate.

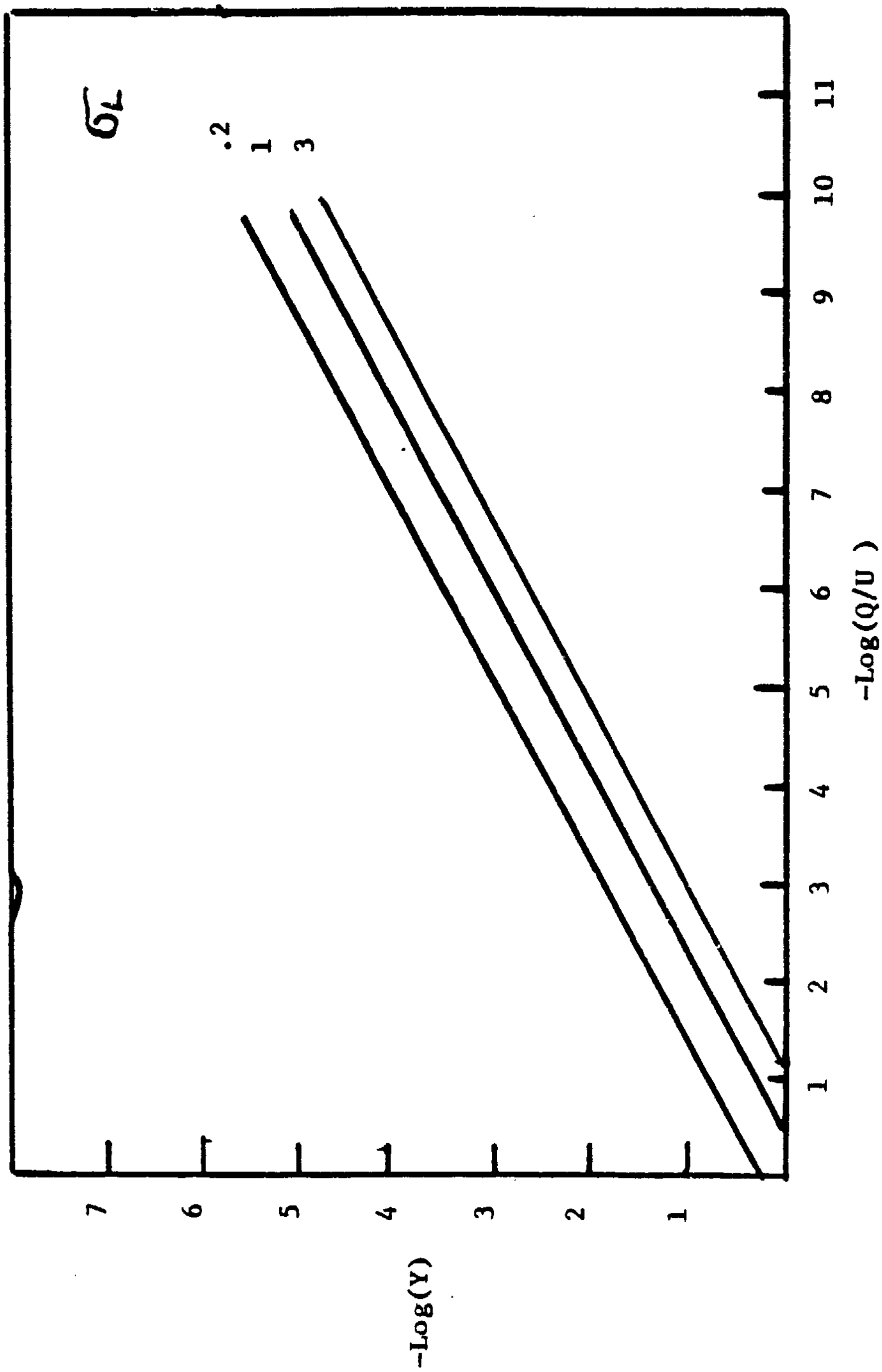

Figure 2. The distance from the surface for the non-dimensional length X/L = .5. The shape factor k = .5. The values of Y were obtained using equation 9c.

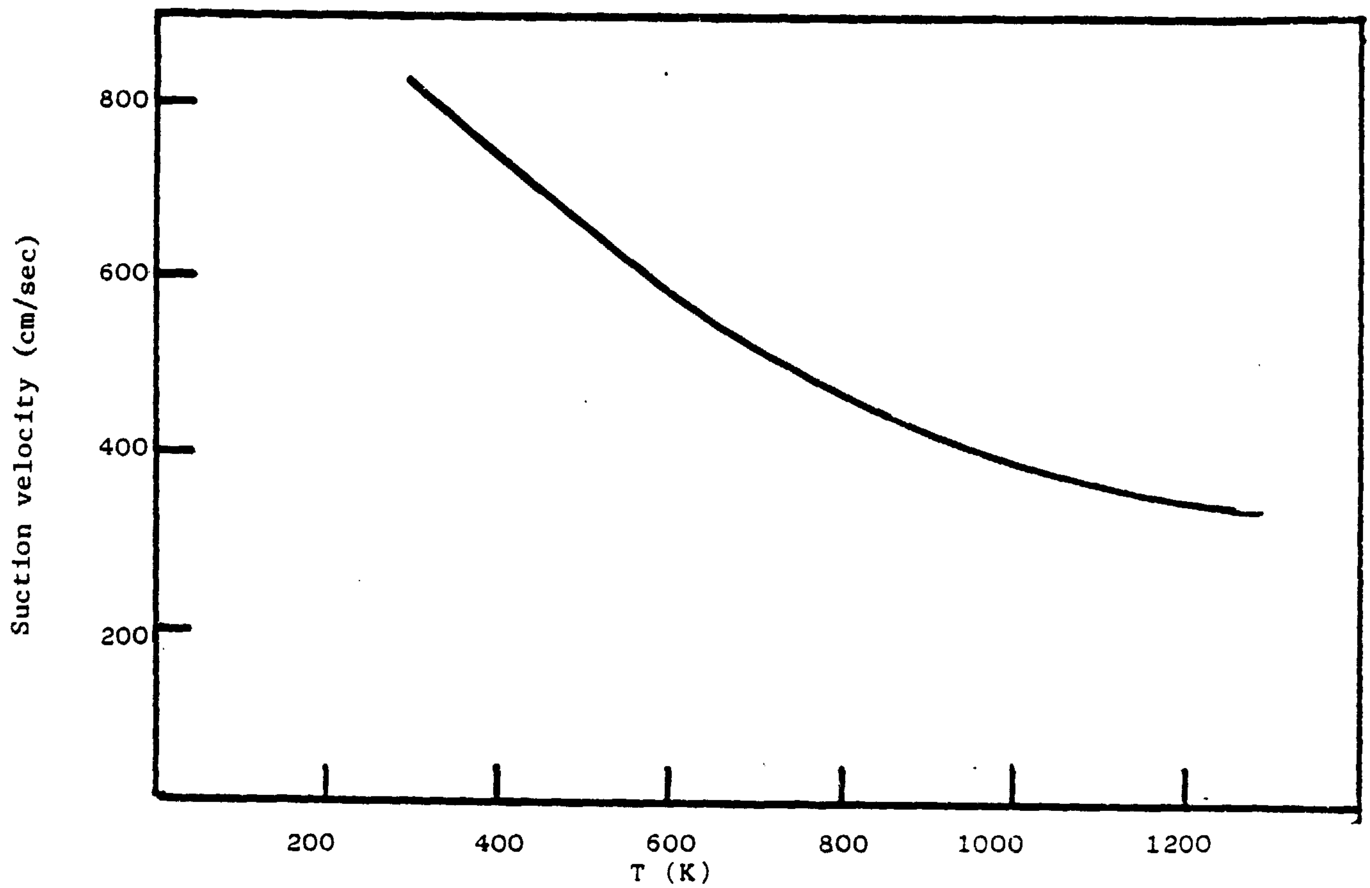

Figure 3. Suction velocity as a function of flow temperature.
Radius = .008 cm, length = 10 cm, Mach # = 5, k = .5,
Pressure = .2.

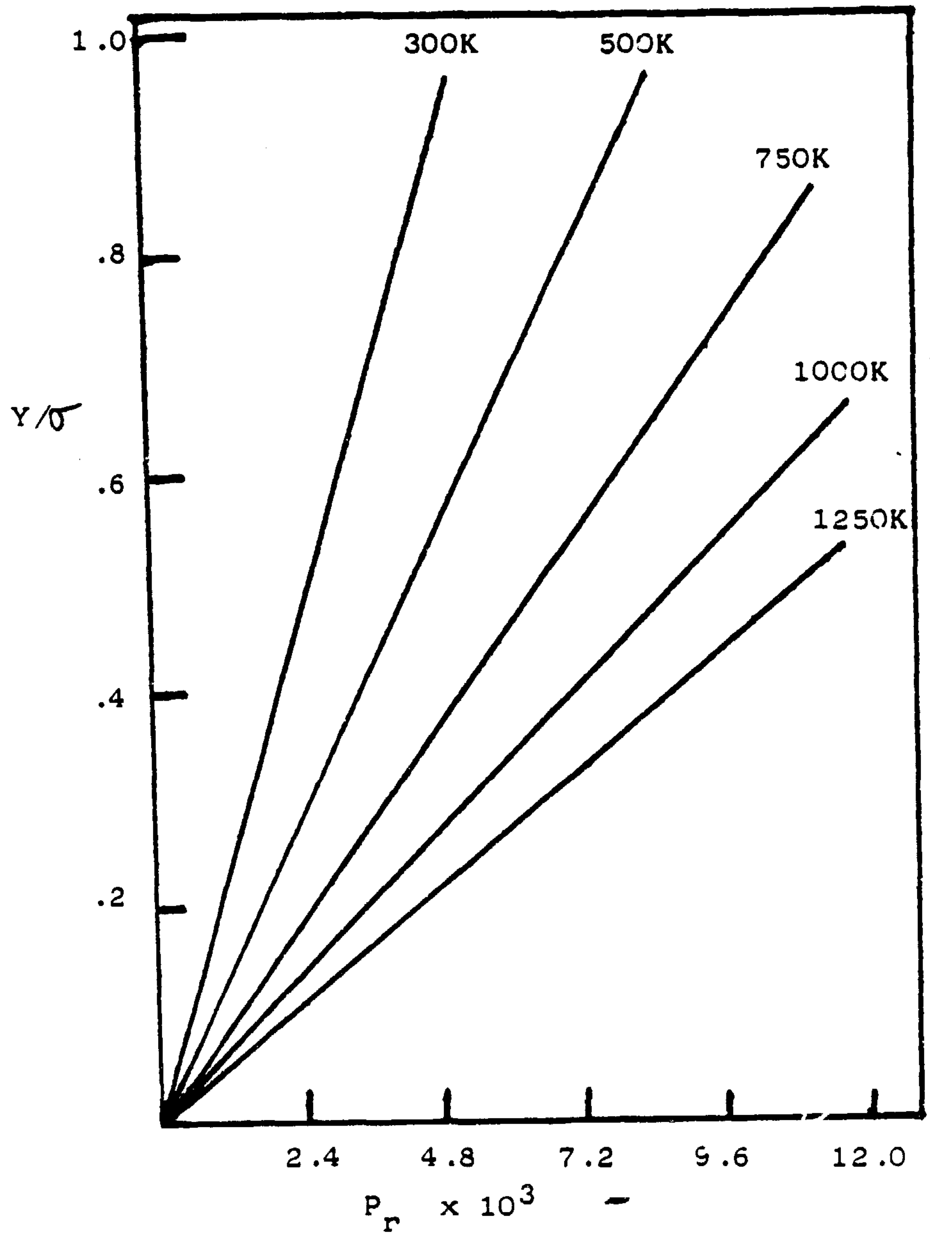

Figure 4. Suction ratio as a function of temperature and reduced pressure (P_r). Radius = .008 cm, length = 10 cm, Edge distance = 10cm, Mach# = 5, k = .5.

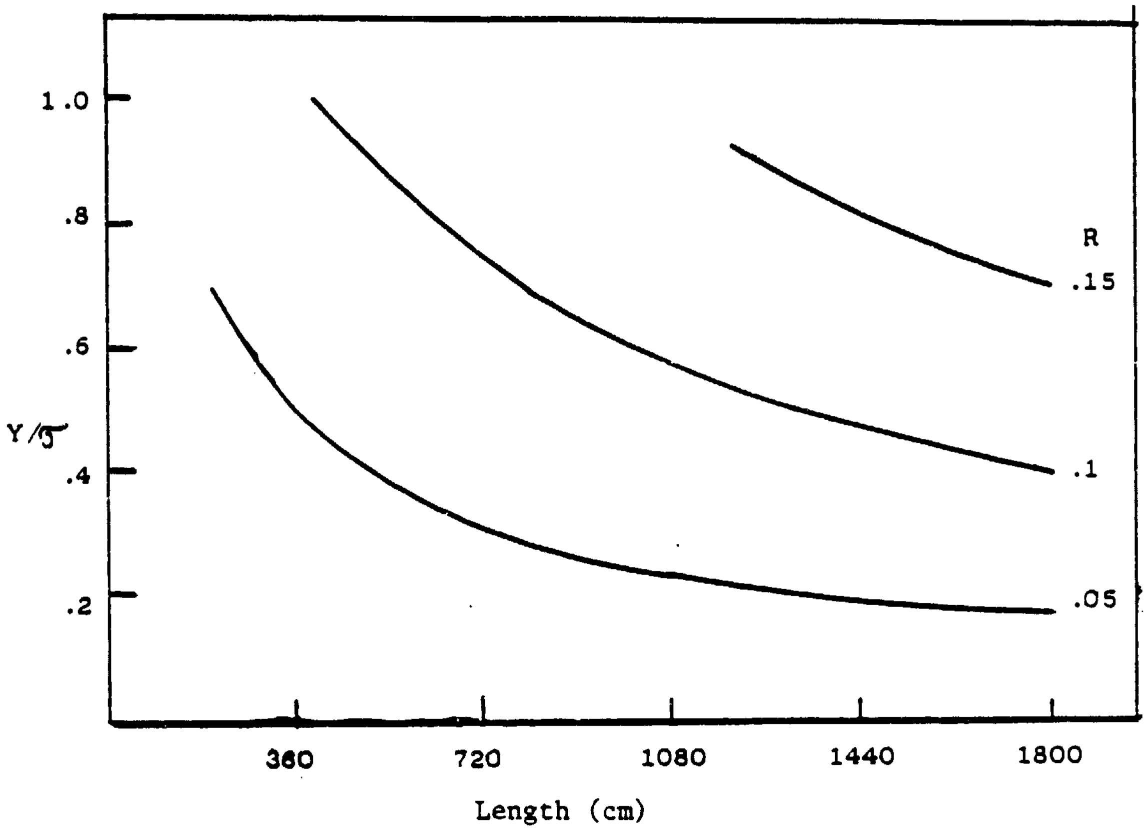

Figure 5. Dependence of suction ratio on tubing length (L) and radius (R). Pressure = .2, Temperature = 750 K, Distance from edge = 10 cm, Mach #5, k = .5.

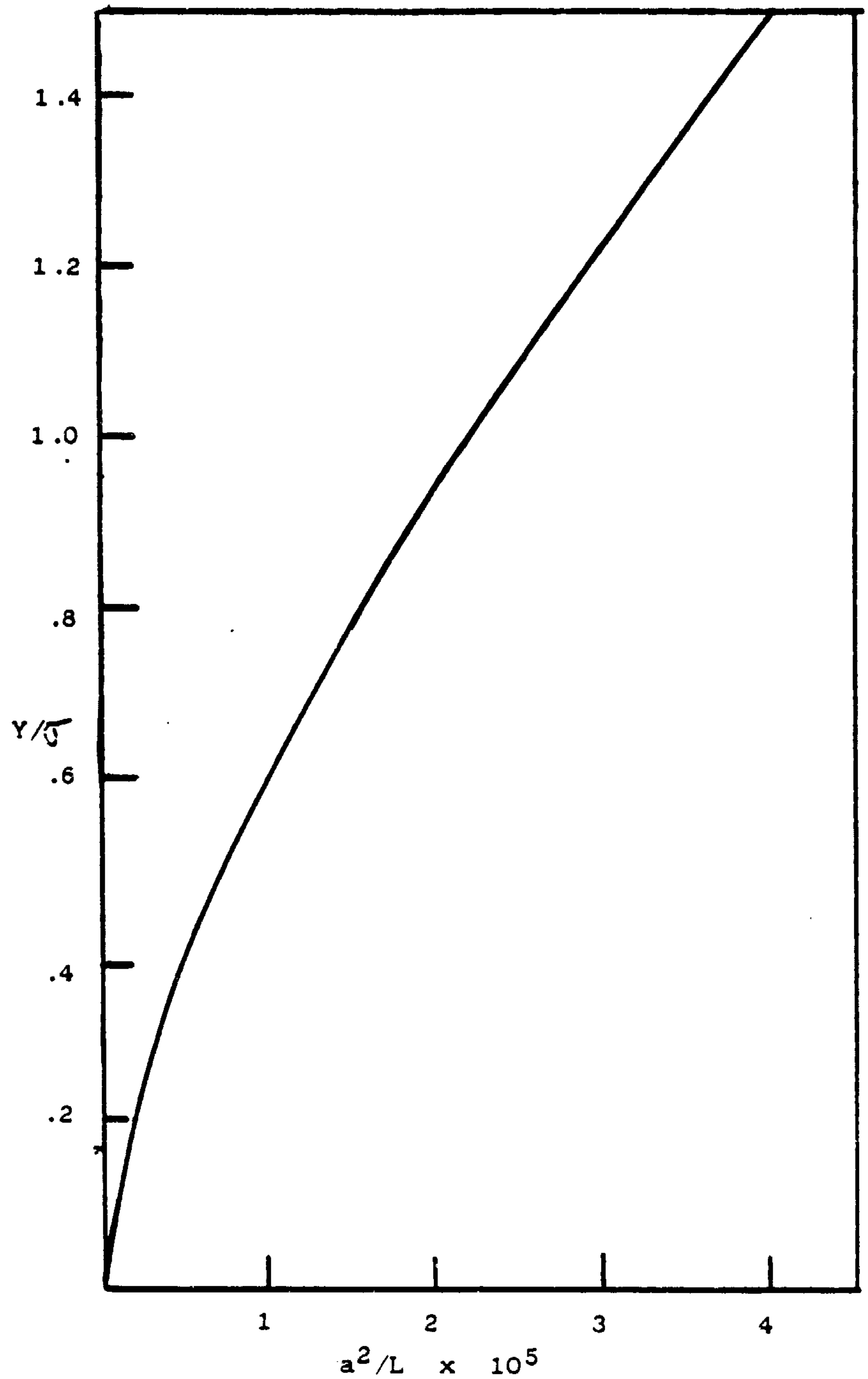

Figure 6. Suction ratio as a function of the ratio of tubing cross-sectional area to tubing length.

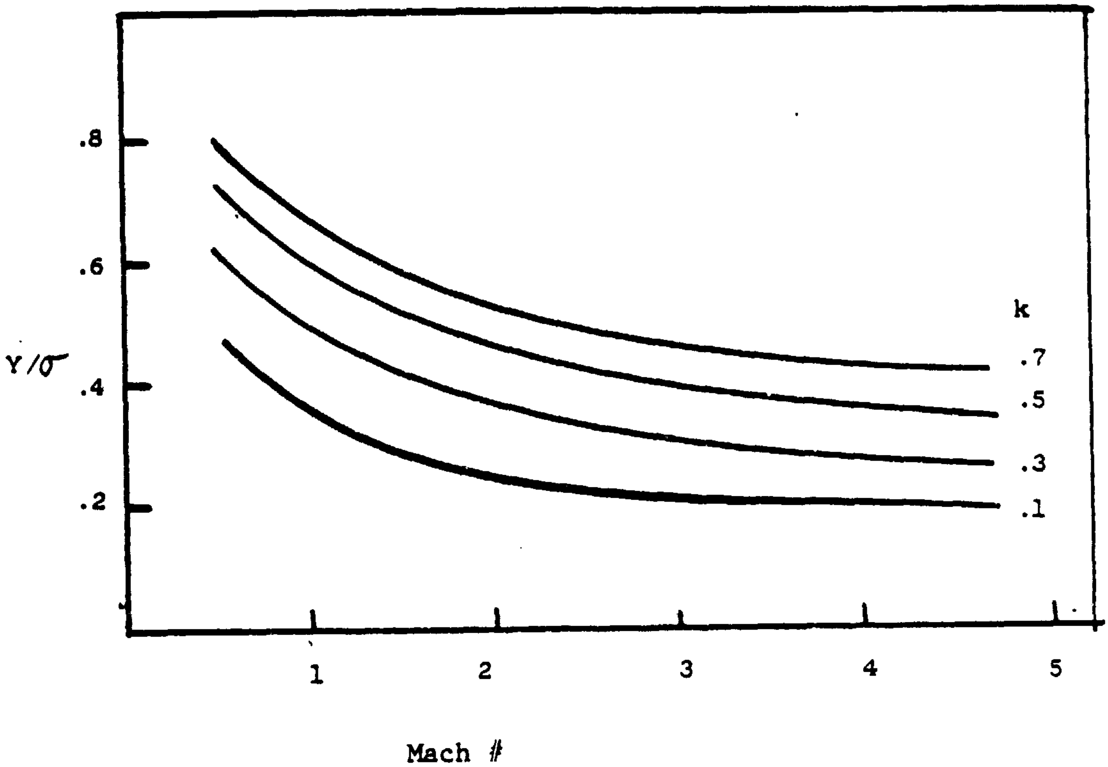

Figure 7. Variation of suction ratio with stream velocity and shape factor. Tube radius = .008 cm, Tube length = 10 cm, Temperature = 1000 K, Inlet Pressure = .2 atm. Distance from edge = 10 cm, Outlet Pressure = 0 atm.