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EFFECTS OF NONEQUILIBRIUM AND MASS TRANSFER ON A BLUNT OGIVE PRESSURE DISTRIBUTION

Clark H. Lewis, John C. Adams, Jr., H. S. Brahinsky, et al.

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

Pressure distributions over a spherically blunted ogive were computed for perfect ($\gamma = 1.4$) gas, equilibrium air, and nonequilibrium inviscid outer flow fields with nonreacting and reacting boundary-layer flow fields. The effects of surface mass transfer and displacement were also included in the nonreacting flow field studies. The results show that for a short (15 nose radii), blunt body at the altitude and velocity conditions considered, the effects of (inviscid and viscous) chemistry on the surface pressure distributions were from about 10 to 20 percent, and the effects of displacement and mass transfer were less than 10 percent in general.

CONTENTS

	<u>Page</u>
ABSTRACT	iii
NOMENCLATURE	vi
I. INTRODUCTION	1
II. CONDITIONS STUDIED	2
III. RESULTS AND DISCUSSION	6
IV. CONCLUDING REMARKS	9
REFERENCES	10

ILLUSTRATIONS

Figure

1. Blunt Ogive Geometry	4
2. Surface Temperature Distributions Used in the Boundary-Layer Calculations	5
3. Surface Mass Transfer Rates Used in the Injection Calculations	5
4. Surface Pressure Distribution for Case A (240,000 ft and 22,000 ft/sec)	6
5. Surface Pressure Distribution for Case B (180,000 ft and 23,000 ft/sec)	7
6. Boundary-Layer Displacement Thickness for Case A (240,000 ft and 22,000 ft/sec)	8
7. Boundary-Layer Displacement Thickness for Case B (180,000 ft and 23,000 ft/sec)	9

TABLE

I. Free-Stream and Stagnation Conditions	3
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NOMENCLATURE

H_e	Stagnation enthalpy
M_∞	Free-stream Mach number
p	Pressure, lb_f/ft^2
Re	Reynolds number
r	Local body radius
r_n	Body nose radius, 3.4 in.
s	Surface distance
T	Temperature, $^\circ\text{R}$
U	Free-stream velocity, ft/sec
v	Normal velocity, ft/sec
z	Axial distance
γ	Ratio of specific heats
δ^*	Displacement thickness, in.
ρ	Density

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o'	Normal shock stagnation
w	Wall
∞	Free-stream

SECTION I INTRODUCTION

The purpose of this study was to determine numerically the effect of chemical nonequilibrium and surface mass transfer on the pressure distribution along the windward streamline of a lifting, relatively blunt, hypothetical reentry vehicle in the earth's atmosphere.

The body chosen was a spherically blunted ogive at two altitude and velocity conditions. The windward streamline of a lifting body was approximated by an axisymmetric body as has been done in several previous studies. The simulated angle of attack was limited by the requirement that the sonic point on the inviscid body surface must lie on the spherical nose, and because of the lifting vehicle body geometry to be simulated, the angle of attack was thus restricted to about 25 deg.

Various numerical methods were used in the study. The ideal gas ($\gamma = 1.4$) blunt body and characteristics used the method developed by Inouye, Rakish, and Lomax (Ref. 1). The equilibrium air calculations used a modification of the method of Lomax et al. as developed by the Space-General Corporation (Ref. 2) with the air properties from the recent work of Hilsenrath and Klein (Ref. 3) and Lewis and Neel (Ref. 4). The inviscid nonequilibrium calculations used the method of Curtis and Strom (Ref. 5). In all three methods, an inverse blunt body solution is obtained, and then a starting line is obtained from the blunt body solution. The method of characteristics is then used in the downstream region of the ideal and equilibrium gas solutions, whereas the solution method of Curtis and Strom uses a series of rays drawn normal to the surface (see Ref. 5).

The nonreacting boundary-layer calculations were based on a modification and extension of the method of Jaffe, Lind, and Smith (Ref. 6). Some of the modifications are described in a paper by Mayne, Gilley, and Lewis (Ref. 7), and the injected gas (CO_2) properties were extended from 6300 to 12,000 °R for purposes of this study.

The nonequilibrium and frozen air boundary-layer calculations were based on a modification of the finite difference method developed by Blottner (Ref. 8). The modifications included the development of a stagnation point solution method from the finite difference scheme and the inclusion of edge properties from the finite-rate inviscid flow field solutions based on Ref. 5.

Since the primary purpose of this study was to investigate the effects of surface mass transfer and nonequilibrium on the surface pressure distribution, some means was needed to determine the effects of displacement and mass transfer on the inviscid flow field. The method used in the nonreacting gas studies (i. e., ideal gas inviscid outer flow field) is described in a paper by Marchand, Lewis, and Davis (Ref. 9). Since no similar techniques exist for the equilibrium and nonequilibrium flow field perturbations, only the nonperturbed solutions are presented.

In the next section, the conditions studied are given, and in the following section the results of the calculations are presented and discussed. Finally a few concluding remarks are given.

SECTION II CONDITIONS STUDIED

2.1 FREE-STREAM AND STAGNATION CONDITIONS

For purposes of this study and comparison, two cases were defined and the conditions are given in Table I. The free-stream conditions were taken from Lewis and Burgess (Ref. 10). The normal-shock stagnation conditions were obtained from either ideal gas relations (ideal), the conditions given by Lewis and Burgess (equilibrium), or the finite-rate blunt body solution (nonequilibrium). The nonreacting stagnation conditions were obtained from the given free-stream pressure, Mach number, stagnation enthalpy, and the properties in the nonreacting boundary-layer program. We see, therefore, a wide variation in stagnation conditions and a lesser variation in free-stream conditions. The free-stream conditions for the nonreacting calculations are given but do not enter the calculations in any way.

Because of machine-time limitations, we were not able to make the nonequilibrium flow field calculations for Case B. However, frozen and nonequilibrium streamtube calculations were made based on the method of Lordi and Mates (Ref. 11) using the ideal gas surface pressure distribution. The stream tube expansion began with the inviscid equilibrium stagnation conditions, whereas the data for Case A were determined from the nonequilibrium stagnation solution. Since no finite-rate flow field calculations exist for Case B, the results based on the procedure described are presented but are otherwise inconsistent with the other calculations.

An effort was made to keep the inviscid and viscous calculations as consistent as possible. Of course, different methods were used in the various calculations which, for example, involved different reaction rates, but an effort was made to match inviscid and viscous flow field calculations rather than, say, use the inviscid ideal gas outer flow with the nonequilibrium boundary-layer solution.

TABLE I
FREE-STREAM AND STAGNATION CONDITIONS

Case A

Altitude = 240,000 ft

$U_\infty = 22,000$ ft/sec

	M_∞	p_∞ , lb/ft ²	$H_\infty \times 10^{-8}$, ft ² /sec ²	T_∞ , °R	$\rho_\infty \times 10^7$, slugs/ft ³	γ_∞	Re_∞ /ft	$T_{0\infty}$, °R	$p_{0\infty}$, lb/ft ²	$\rho_{0\infty} \times 10^7$, slugs/ft ³	$\gamma_{0\infty}$
Ideal	23.221	0.07019	2.44244	372.266	1.0988	1.4	8,480.626	40,600	48.8	7.0	1.4
Equilibrium	23.221	0.07043	2.44244	372.266	1.0988	1.4	8,480.626	10,207.3	51.5238	2 18.909	1.1174
Nonequilibrium or Frozen	23.221	0.07088	2.44244	372.266	1.0988	1.4	8,480.626	16,500	50.2	12.8286	
Nonreacting	23.221	0.0703	2.44244	298.6	1.3865	Ideal 1.135 Equil 1.1174	10,340	11,200	51.5238	26.8	Ideal 1.135 Equil. 1.1174

91.308 ↑ 21.492

Case B

Altitude = 180,000 ft

$U_\infty = 23,000$ ft/sec

	M_∞	p_∞	H_∞	T_∞	ρ_∞	γ_∞	Re_∞	$T_{0\infty}$	$p_{0\infty}$	$\rho_{0\infty}$	$\gamma_{0\infty}$
Ideal	21.441	0.9083557	2.673755	478.548	11.05791	1.4	72,721.89	27,200	538	115.3	1.4
Equilibrium	21.441	0.9083557	2.673755	478.548	11.05791	1.4	72,721.89	11,647.38	567.4798	284	1.1333
Nonequilibrium or Frozen	21.441	0.9083557	2.673755	478.548	11.05791	1.4	72,721.89				
Nonreacting	21.441	0.9083557	2.673755	368.4	14.35	1.1333	92,500	11,660	567.4798	284	1.1333

459.1244 229.5188

2.2 BODY GEOMETRY

The geometry considered is shown in Fig. 1. The body consists of a spherical nose, a circular arc and conical afterbody of 21-deg half-angle (the simulated angle of attack). The axial and radial coordinates are nondimensionalized by the nose radius (3.4 in.).

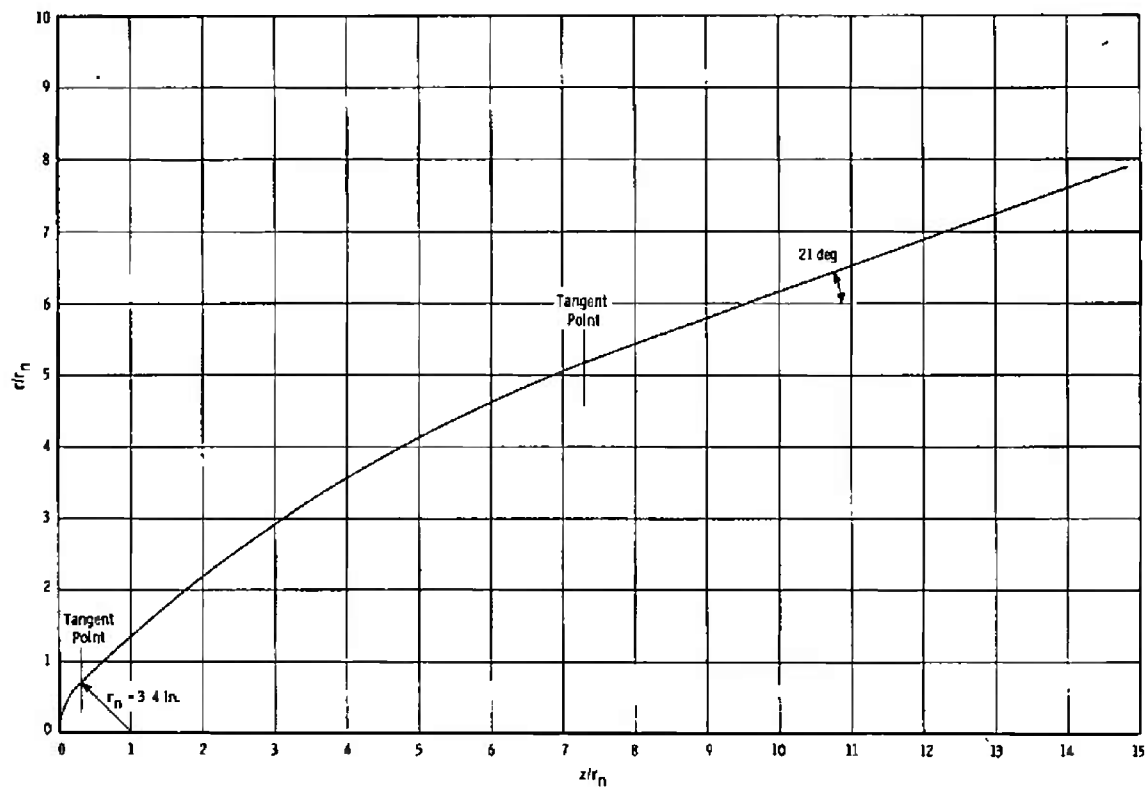


Fig. 1 Blunt Ogive Geometry

2.3 SURFACE TEMPERATURE DISTRIBUTION

The assumed surface temperature distributions are given for both Cases A and B in Fig. 2.

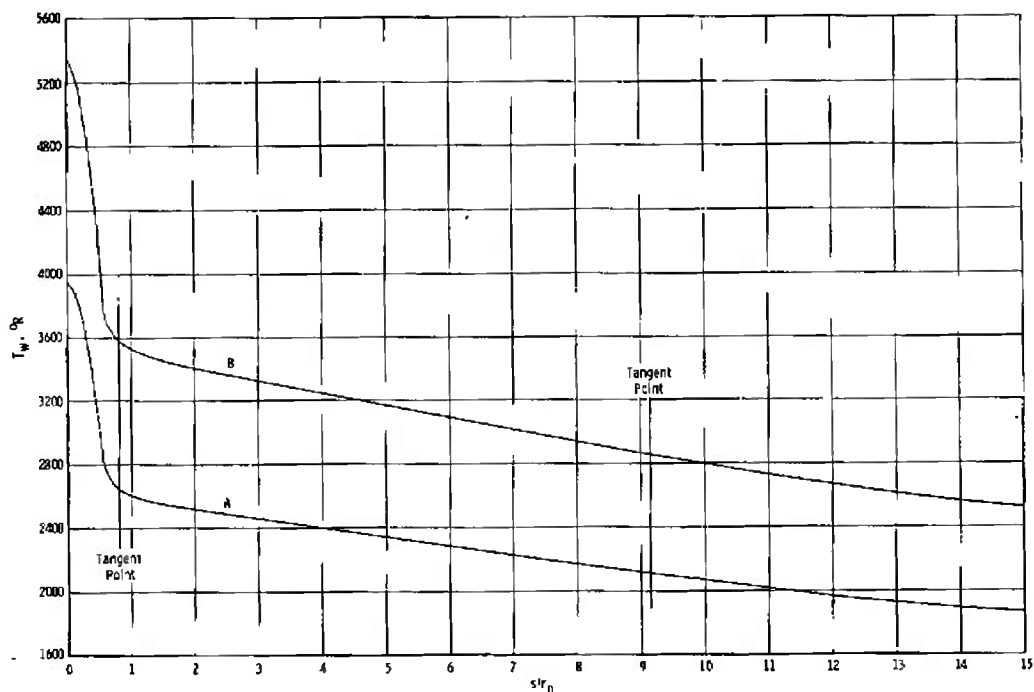


Fig. 2 Surface Temperature Distributions Used in the Boundary-Layer Calculations

2.4 SURFACE MASS TRANSFER DISTRIBUTIONS

The assumed mass transfer (CO_2) distributions used in the nonreacting boundary-layer calculations are given in Fig. 3.

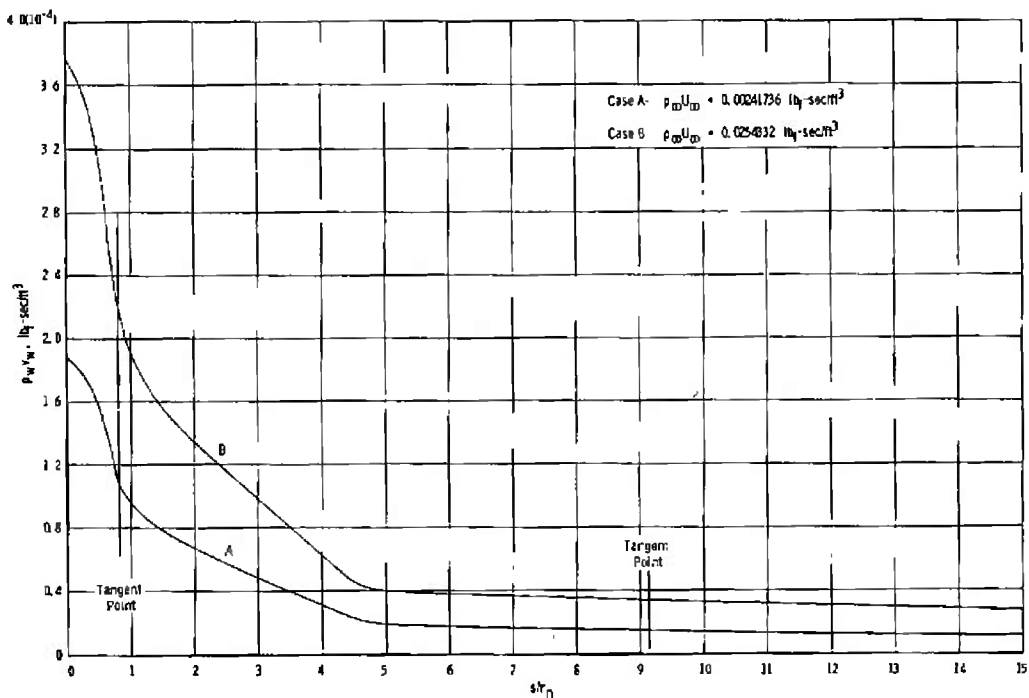


Fig. 3 Surface Mass Transfer Rates Used in the Injection Calculations

SECTION III

RESULTS AND DISCUSSION

The inviscid and viscous-induced surface pressure distributions are shown in Figs. 4 and 5 for Cases A and B. The term 0th iteration denotes the inviscid surface pressure distribution without boundary layer, and 1st iteration denotes one perturbation of the inviscid outer flow caused by displacement. As previously noted, only the ideal inviscid flow field was perturbed with and without injection.

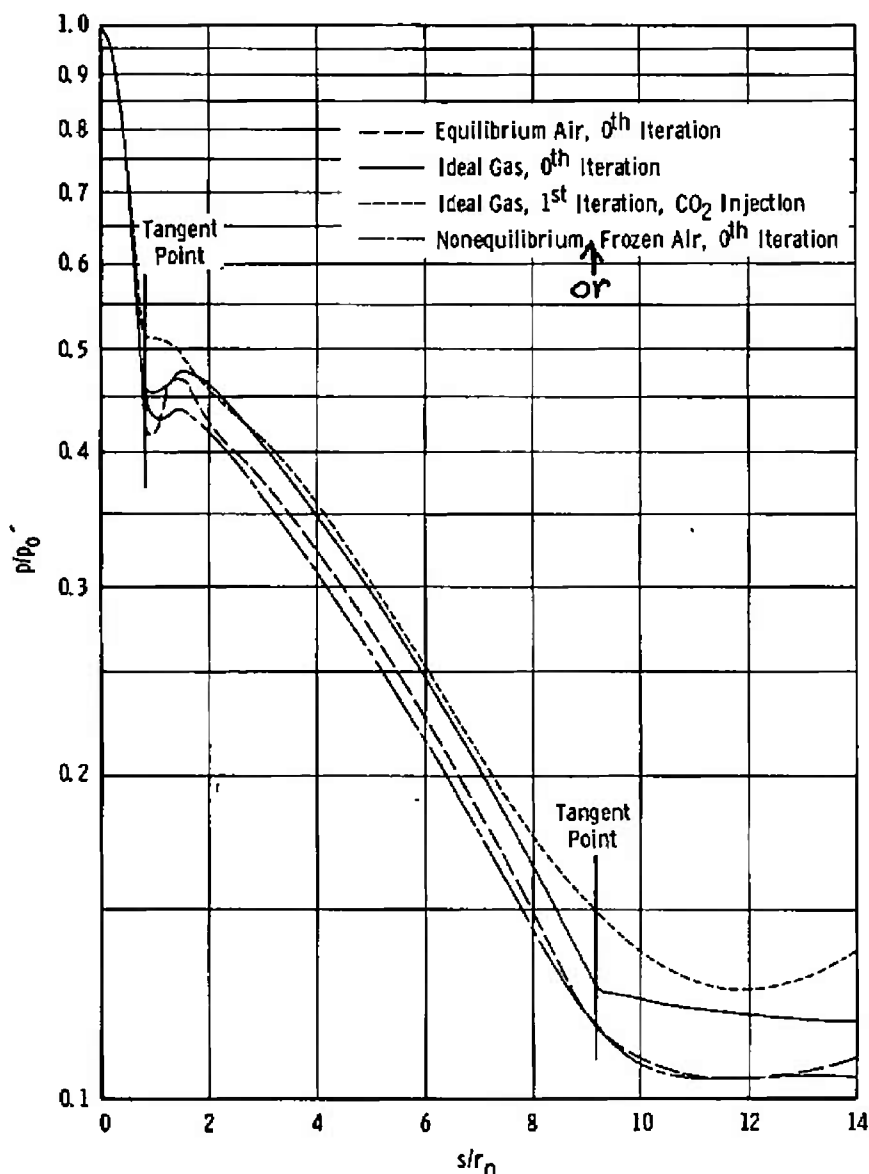


Fig. 4 Surface Pressure Distribution for Case A (240,000 ft and 22,000 ft/sec)

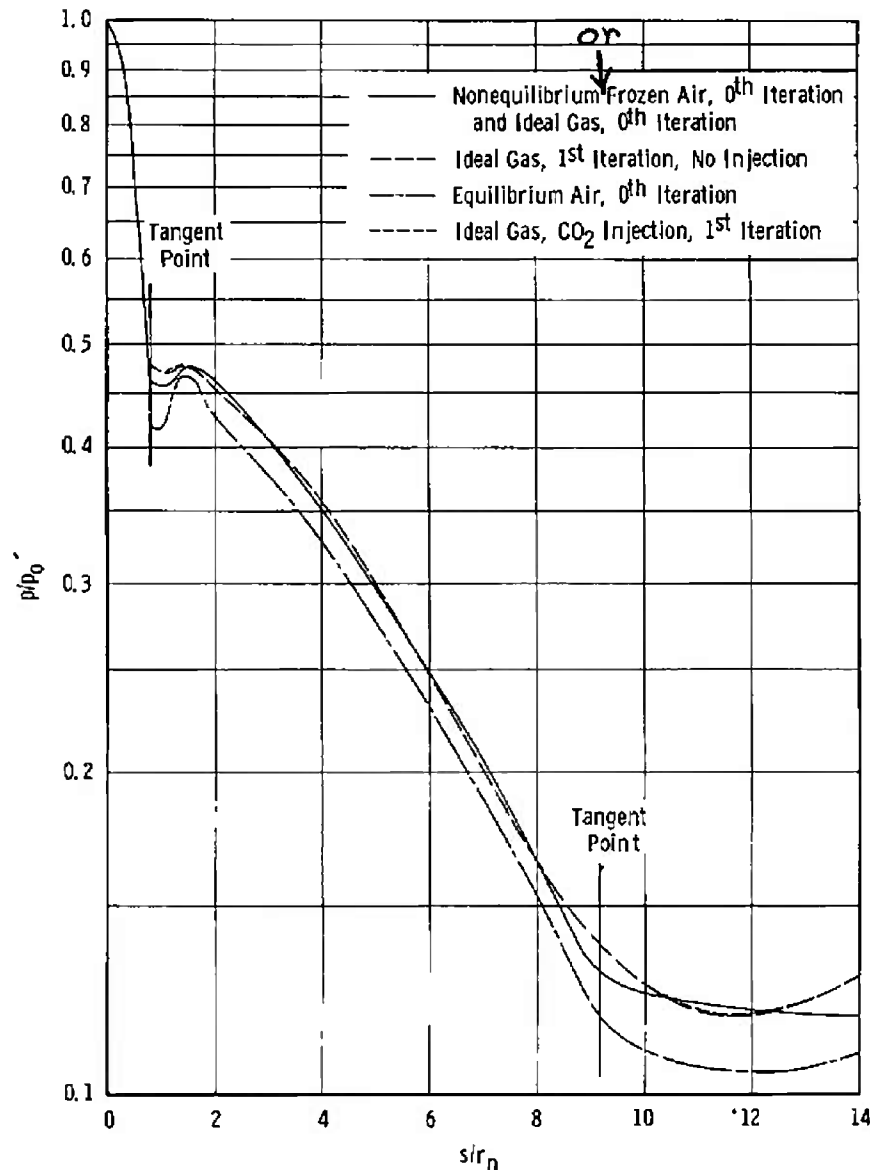


Fig. 5 Surface Pressure Distribution for Case B (180,000 ft and 23,000 ft/sec)

The effects of chemistry (equilibrium or finite rate) and injection have a very small effect on the pressure distribution over the spherical nose. The largest effects occur in the region of the overexpansion of the pressure just downstream of the first tangent point. Here the effects of chemistry and mass transfer are strongest on the flow field, and the pressure is strongly affected by small changes in streamline direction caused by displacement and mass transfer. Of course, it would be interesting to investigate the effects of displacement and mass transfer in the equilibrium and nonequilibrium cases; however, at the present time procedures have not been developed for these methods.

The results for Case B are given in Fig. 5. As noted previously, the nonequilibrium flow field results for this case were not complete because of machine-time limitations, and the finite-rate boundary-layer calculations were based on the 0th iteration ideal ($\gamma = 1.4$) flow field surface pressure distribution. For this case, the effects of displacement were small, and the effects of mass transfer were negligible by comparison of the viscous-induced pressure increment with and without mass transfer.

For the body and free-stream conditions studied, the only significant second-order boundary-layer effect is displacement. Therefore, it is interesting to compare the effects of chemistry and mass transfer on the displacement thickness distribution for the cases studied.

The results for Case A are shown in Fig. 6. All results are based on the inviscid pressure distribution without any viscous (displacement) effect; therefore, the comparisons are on the same basis, but the effects of chemistry on the inviscid as well as viscous flow fields are included. We see a large overall effect (about a factor of six at the second tangent point). The effects of the lower inviscid equilibrium pressure distribution are seen by comparison of the equilibrium and ideal CO_2 injection results. Since the inviscid equilibrium pressure is minimum, the local Reynolds number is a minimum and the second-order displacement effect is a maximum all other being equal.

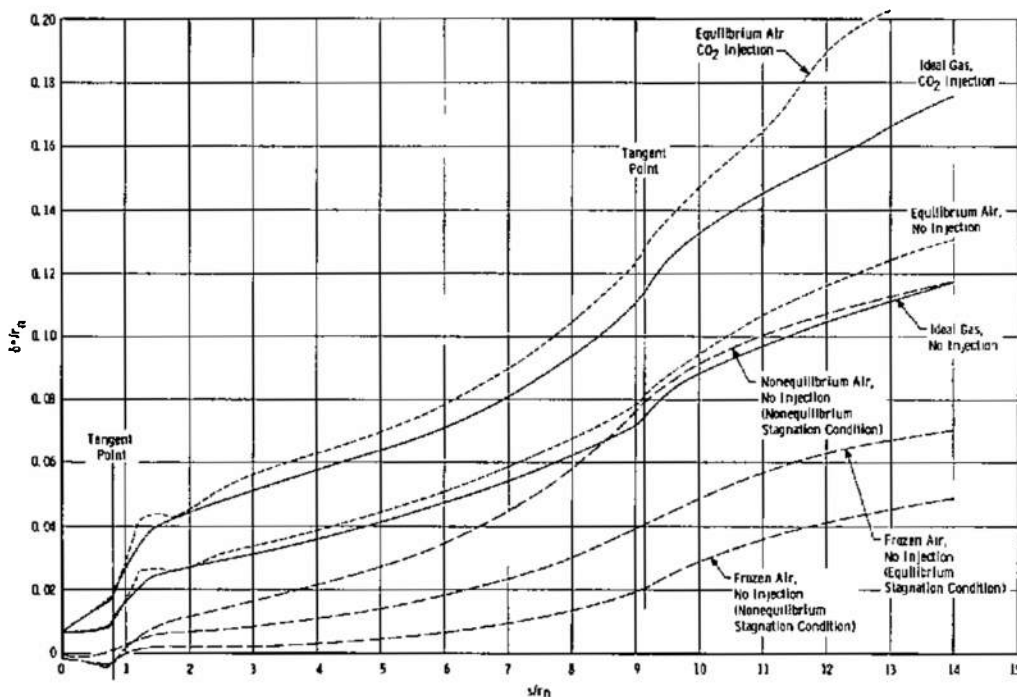


Fig. 6 Boundary-Layer Displacement Thickness for Case A (240,000 ft and 22,000 ft/sec)

The Case B results are shown in Fig. 7. The trends of the results are similar to Case A except that the effects of higher Reynolds number reduce the displacement effect.

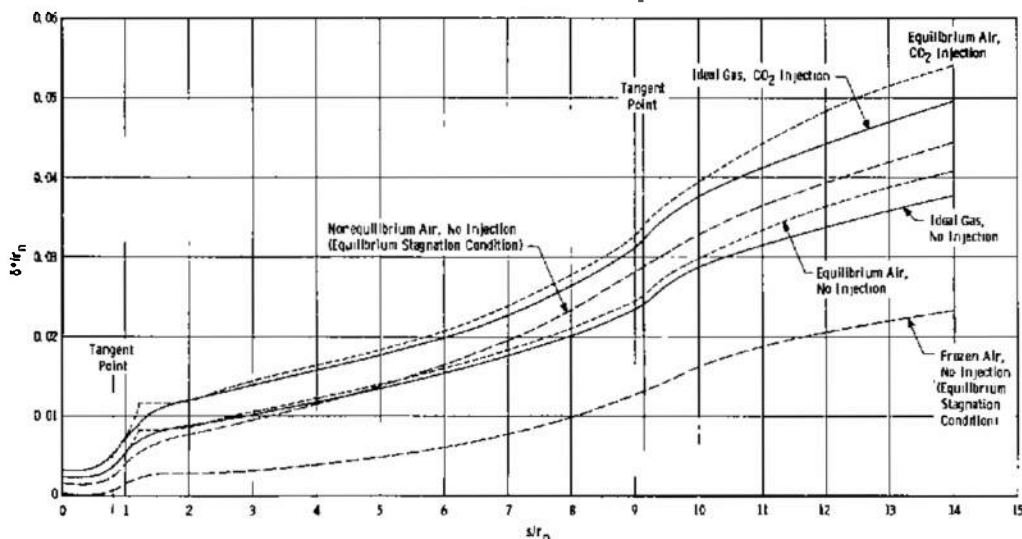


Fig. 7 Boundary-Layer Displacement Thickness for Case B (180,000 ft and 23,000 ft/sec)

SECTION IV CONCLUDING REMARKS

A blunt ogive at two altitude-velocity conditions was studied, and on the basis of the results the following remarks are made.

1. For the short, blunt body at the altitude and velocity conditions studied, the effects of (inviscid and viscous) chemistry on the surface pressure distributions were relatively small (about 10 to 20 percent).
2. The effects of displacement on the surface pressure were smaller in general (less than 10 percent over most of the body).
3. At the higher Reynolds number, the effect of displacement was very small and the effects of mass transfer were negligible on the surface pressure distribution.

In summary, it can be said that for the conditions considered, small second-order effects including chemistry were found. However, a word of caution should be noted. First, the body was short and blunt, thus minimizing the effects of chemistry, mass transfer and viscous displacement. Secondly, because of the restriction that the inviscid sonic point

on the body must lie on the sphere, the angle of attack was limited to less than 25 deg, and a specific angle of attack of 21 deg was chosen. If higher altitude conditions at a smaller angle-of-attack condition had been chosen, the effects would have been larger. Finally, the effects of chemistry and displacement are reduced by increasing the pressure, and the highest pressure condition (most windward streamline) was investigated. The viscous and chemical effects would be larger off this streamline. Thus the effects considered were small, but extrapolation and generalization should be based on more extensive calculations and a parametric study.

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Pressure distributions over a spherically blunted ogive were computed for perfect ($\gamma = 1.4$) gas, equilibrium air, and nonequilibrium inviscid outer flow fields with nonreacting and reacting boundary-layer flow fields. The effects of surface mass transfer and displacement were also included in the nonreacting flow field studies. The results show that for a short (15 nose radii), blunt body at the altitude and velocity conditions considered, the effects of (inviscid and viscous) chemistry on the surface pressure distributions were from about 10 to 20 percent, and the effects of displacement and mass transfer were less than 10 percent in general.

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