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Aerodynamics of 3-Dimensional Bodies in Transitional Flow

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Abstract

Based on considerations of fluid dynamic simulation appropriate to hypersonic, viscous flow over blunt-nosed lifting bodies, a method was presented earlier by the author for estimating drag coefficients in the transitional-flow regime. The extension of the same method to prediction of lift coefficients is presented in this paper. Correlation of available experimental data by a simulation parameter appropriate for this purpose is the basis of the procedure described. The ease of application of the method makes it useful for preliminary studies which involve a wide variety of 3-dimensional vehicle configurations or a range of angles of attack of a given vehicle.

Nomenclature

C_D	= drag coefficient
C_e	= $(\mu_e/\mu_\infty)(T_\infty/T_e)$
C_L	= lift coefficient
C_p	= pressure coefficient $(p - p_\infty)/q_\infty$
D	= drag
H	= enthalpy
L	= lift
M	= Mach number
PFA	= projected frontal area
PPA	= projected planform area
P_n	= similarity parameter (Eqs. 2 and 5)
p	= static pressure
q	= dynamic pressure
Re_o	= $Re_\infty(\mu_\infty/\mu_o)$
s	= streamwise wetted length
s*	= characteristic length (Eq. 3)
T	= temperature
$\underline{U}$	= velocity
$\overline{V}_e$	= $M_e(C_e/Re_e)^{1/2}$
WA	= wetted area
α	= angle of attack

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γ = ratio of specific heats
η = angle between surface unit normal and free-stream velocity vectors
μ = absolute viscosity
ν = kinematic viscosity (μ/ρ)
ρ = density
ω = exponent in viscosity-temperature relation

Subscripts
e = edge of boundary layer
fm = free molecular flow
i = inviscid flow
o = stagnation region
w = wall
∞ = freestream

Introduction

Many experimental and theoretical investigations of the drag of simple shapes in hypersonic, rarefied flow have been reported. Very few reports on lift and static stability have appeared. During this time it has been recognized that even the best laboratory facilities available for this work did not meet all of the desired simulation requirements, and computational techniques had not been developed to the level necessary for dealing with complex shapes having unknown gas/surface interaction, slip-flow, and nonequilibrium gas processes. It is remarkable that adequate re-entry vehicles have been designed on the basis of this earlier research. That continues the history of aeronautics which also is a record of successful but not generally optimal aircraft produced despite obvious deficiencies in the theoretical and laboratory base for the work.

The low air densities that characterize the transitional flow flight regime lead to low aerodynamic forces and heating. For many vehicles, that makes precision in aerodynamic predictions of lesser importance. Large errors in coefficients lead to only small errors in absolute magnitudes of forces or heating rates. This had made many aerospace designers indifferent to rarefied flow phenomena despite the rather spectacular changes in aerodynamic coefficients that often occur in the transitional regime. However, aerospace vehicles of increased aerodynamic and structural sophistication, capable of maneuvering through use of aerodynamic controls, and dependent upon much more accurate predictions of fluid dynamics for safe and efficient operation are now of greater concern. Lift, lift-to-drag ratio, and stability have assumed increased importance.

The prediction of aerodynamic, or more generally gasdynamic forces under hypervelocity, rarefied flow conditions is based upon approximate theoretical methods or correlations of the relatively small collection of relevant experimental data. At present, and probably for several more years, the two avenues to follow are (1) the use of experimental data in conjunction with carefully chosen simulation and scaling parameters and (2) the direct simulation Monte Carlo (DSMC) computational technique. The latter is a powerful tool, but it requires certain arbitrary inputs; the necessity to assume a gas/surface interaction model perhaps is the main point in this case. On the other hand, the shortcomings of wind tunnels and other laboratory devices in regard to duplication of in-flight real gas and gas/surface effects are well known and do not need repeating here. Complex configurations, with interfering flows associated with different components of the vehicle usually are no problem in wind tunnels. However, inability to fully duplicate the full-scale vehicle's flight environment, possibly including the gas/surface interaction, raises various questions. Thus, the data must be scaled or extrapolated with care, to say the least.

This paper addresses the problem of predicting lift and lift-to- drag ratio of aerospace craft in transitional flow. The approach used earlier by this author[1] in scaling drag coefficients is extended for the present purpose. That may be described as the correlation of normalized aerodynamic coefficients with a simulation parameter which is designed to account for the principal flow phenomena that cause the coefficients to vary. The derivation of this simulation parameter is fully described in Ref. 1, and only its extension to include lift coefficients is covered here.

Lift in Hypersonic Transitional Flow

In marked contrast to the amount of data now available on drag of bodies in transitional flow, very few measurements of lift have been published. Several reports from the Arnold Engineering Development Center in the 1960's (e.g., Refs. 2-3) contain the only wind tunnel data on lift, drag, and pitching moment in the midst of the transitional regime that the author has knowledge of. Space Shuttle re-entry data 4, 5 are now available and are, of course, extremely valuable because no wind tunnels can fully match the flow conditions of hypersonic re-entry. No theoretical/numerical computations of these coefficients for lifting bodies throughout the transitional regime are known to the writer, although it would seem likely that further development of the DSMC method will soon lead to some results on this problem. Therefore, it has been necessary to work with only the experimental data of Refs. 2-5.

The Parameters

The simulation parameter described in Ref. 1 was devised as a hybrid of $\overline{V}_e$ and Re_o with the purpose of obtaining a parameter suitable for scaling viscous,hypersonic flow effects on typical hypersonic re-entry configurations, either lifting or non- lifting. These were visualized as blunted, cold-wall bodies at varying angles of attack. The characteristic length in the parameter was taken to be a modified wetted length in the streamwise direction. The modification was made to obtain a length more representative of the overall body. For example, a simple wetted length or body diameter tells nothing about fineness ratio or angle of attack of the body. Yet it is well known that both projected frontal area and wetted area are significant in regard to forces on bodies in transitional flow. Therefore, a "shape factor" was applied to the wetted length to yield the characteristic length.

To briefly summarize, in Ref. 1, it is shown that the normalized form of drag coefficient,

$$\overline{C}_D = (C_D - C_{Di})/(C_{Dfm} - C_{Di}) \qquad (1)$$

of a variety of practical vehicle shapes is correlated with a simulation parameter defined as follows:

$$Pn = \sqrt{(U/\nu)_\infty \, s^* \, (H_\infty/H^*)^\omega} \qquad (2)$$

$$s^* = s\sqrt{PFA/WA} \qquad (3)$$

$$H_\infty/H^* = [H_\infty/(0.2H_0 + 0.5H_w] \qquad (4)$$

$\omega \approx 0.63$ for high-stagnation-temperature conditions in air or N_2

Note that PFA was denoted as CSA in Ref. 1. The change to PFA makes the terminology more precise. Also note that the shape factor, $\sqrt{PFA/WA}$, is empirically based and therefore provisional.

The alteration proposed here for the accommodation of both drag and lift by the same basic parameter is to now define the pair,

$$Pn_D = \text{drag parameter in Eq. (2)} \qquad (5a)$$

$$Pn_L = Pn_D\,(PPA/PFA)^{1/4} \qquad (5b)$$

Thus, for correlating lift coefficients, the shape factor is based upon projected planform area (PPA), while projected frontal area (PFA) is retained for correlating drag coefficients. The counterpart of Eq. (1) in the case of lift is

$$\overline{C}_L = (C_L - C_{Li})/(C_{Lfm} - C_{Li}) \qquad (6)$$

It will be noticed that the form of Eqs. (1) and (6) encourages scatter in the correlation of experimental data when C_D or C_L is close to the corresponding value for near-inviscid flow, i.e., at large Pn_D or Pn_L. That deficiency is not as serious as it may seem at first, because the designer often will have both experimental and theoretical results available for the higher Reynolds number, continuum, viscous-flow part of the transitional regime for which the scatter may be troublesome.

There are other features of the normalized coefficients that must be pointed out. These concern the specific bases of the inviscid- and free-molecular-flow coefficients used in this paper. The use of other approaches to obtaining these "baseline" coefficients and then combining those results with the $\overline{C}_D$ or $\overline{C}_L$ from the correlations of Ref. 1 or this paper could easily lead to considerable error in the final result. It should be noted that, for all cases in this paper either the modified Newtonian theory or an experimental high Reynolds number

C_{Li} has been used. In the first instance, C_{Li} has been calculated on the basis of a windward surface pressure coefficient,

$$Cp = K \cos^2 \eta \qquad (7)$$

where, following Lees[6]

$$K = (\gamma + 3)/(\gamma + 1) \qquad (8)$$

is chosen for blunt bodies with detached shock waves at large Mach numbers. The conventional assumption, Cp = 0 is made for leeward surfaces. The user of the correlations must not substitute an experimental value for the inviscid term unless it is essentially free of viscous-flow influence, i.e., a very high Reynolds number result. An admonition also is necessary concerning use of a more sophisticated and perhaps more accurate calculation for obtaining C_{Di} or C_{Li}. If any of these improvements are attempted, the correlation curve should also be adjusted by recalculation of the normalized coefficient on the basis of the same inviscid coefficient. A similar warning applies to any changed basis for obtaining the coefficient for free molecular flow, as discussed below.

The values of C_{Dfm} or C_{Lfm} are based upon the gas/surface interaction model of fully accommodated, completely diffuse reemission. This is the most common model assumed, even through it is well known that some degree of specular remission and less- than-complete accommodation are more realistic assumptions. Blanchard[5] has deduced from NASA Space Shuttle flight data that approximately 90% energy accommodation and on the order of 10% specular reflection would lead to the best agreement of conventional free-molecular theory[7] and flight results for lift- to-drag ratio. It is worth noting that these small changes in gas/surface interaction parameters correspond to very large percentage changes in L/D. In any event, the basis for $\bar{C}_D$ and $\bar{C}_L$ must be kept in mind and consistency in the use of inviscid and free molecular coefficients is essential.

Correlation of Data

Not only is the amount of data on lift in transitional flow small, but accuracy is also a concern because of the low forces acting in rarefied flows. Nevertheless, several sets of data are available.[2-5] These have been normalized according to the procedure described and the results are plotted in Fig. 1. The solid curve in Fig. 1 is the same curve shown in Ref. 1 where only drag coefficients were correlated. It is not clear if the points for the experimental $\bar{C}_L$ indicate that a different curve for lift coefficients is necessary. If a separate curve for $\bar{C}_L$ were drawn, it would consist of a fairing through the points for the STS orbiter.

There is evidence that drag coefficients of slender, sharp-nosed bodies at low angles of attack may exceed the free-molecular level in the near-free-molecular or first-collision regime. Therefore, the part of the curve at very low Pn's is uncertain in regard to both level and suitability of a single curve for both $\bar{C}_D$ and $\bar{C}_L$ of bodies fitting that description.

It was stated earlier that blunt-nosed bodies of the type that may be considered for most lifting re-entry vehicles are the primary focus of this paper. However the experimental C_L for a sharp, 18-deg apex angle cone at 20-deg angle of attack was compared with the predicted C_L based on Fig. 1 as a test case. These experimental data had not been included in the preparation of Fig. 1. When the predicted C_L is based on the solid-line curve in Fig. 1, the error in C_L at $Pn_L = 19.2$ is +5% and at $Pn_L = 9.5$ it is +10%. If a revised curve for $\overline{C_L}$, passing through the STS points in Fig. 1 is used, these errors in C_L become 0% and +7%, respectively. In both cases, the experimental uncertainty is at least as great as the discrepancies cited.

Considering the limited data, uncertainty in those data, and the inherent limitations on a correlation of the type presented, an anticipated uncertainty in C_D or C_L of approximately ±10% seems justified at this time. Thus, it is suggested that Fig. 1 represents a useful tool for preliminary design studies wherein numerous variants may be screened, and for other problems where wind tunnel experiments or CFD solutions are not feasible.

Application to AFE Spacecraft

There is current interest in spacecraft which will utilize aerodynamic lift to transfer payloads between different orbits. To obtain flight data on one vehicle design, an Aeroassist Flight Experiment (AFE) is being considered by NASA. A brief description of the configuration and its trajectory are given in Ref. 8, where DSMC calculations of drag coefficient of an axisymmetric approximation to the AFE are also presented. Figure 2, from Ref. 8, shows the elevation or side view of the AFE and the trajectory. A more detailed description of this configuration and discussion of its advantages are in Ref. 9.

With the use of the trajectory information in Ref. 8 and supplemental information from Robert C. Blanchard of NASA Langley Research Center, the values of Pn_D and Pn_L have been computed. Corresponding values for $\overline{C_D}$ and $\overline{C_L}$ were taken from Fig. 1, using the curve shown. Experimental data for C_{Di} and C_{Li} at high Reynolds number and computed C_{Dfm} and C_{Lfm} for fully accommodated, diffuse reemission were taken from unpublished NASA sources. The results for C_D, C_L, and L/D appear in Figs. 3-5.

On Fig. 3, for qualitative comparison, the results from Ref. 8 are also shown. It must be emphasized that the DSMC calculation was carried out for an axisymmetric shape which approximates the actual AFE design. That was done to simplify and shorten the computation, according to Ref. 8, and it is not known how much that may have affected the results. It is noteworthy that the major real gas effects were modeled in the calculation, but the importance of those effects on overall aerodynamic forces in rarefied flow is not yet fully evaluated. Simply based on Eqs. (7-8), it is inferred that C_p on windward surfaces is increased by real gas processes which effectively lower the ratio of specific heats. However, when densities are very low, thermo-chemical-kinetic processes may be nearly frozen. Therefore, no conclusions regarding accuracy can be justified on the basis of Fig. 3, but it may be appropriate to view Fig. 3 as indicative of the current state of the art of predicting transitional, hypersonic drag coefficients by different approaches. At this time the writer is not aware of other published C_L or L/D estimates for the AFE vehicle although work toward that end undoubtedly is in progress.

Acknowledgments

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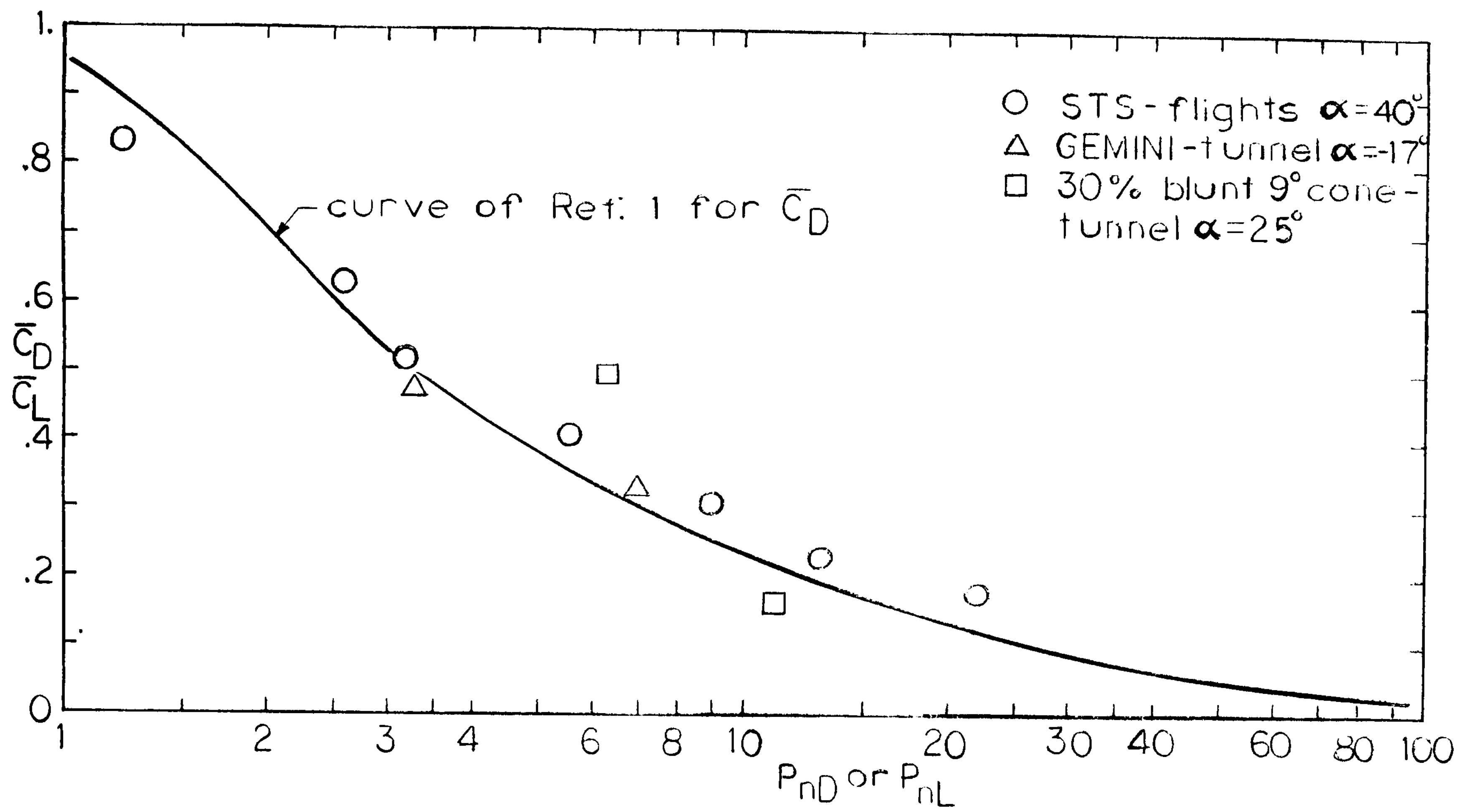

Figure 1. Normalized lift coefficients from flight and wind tunnel compared to the correlation curve for drag presented in Reference 1.

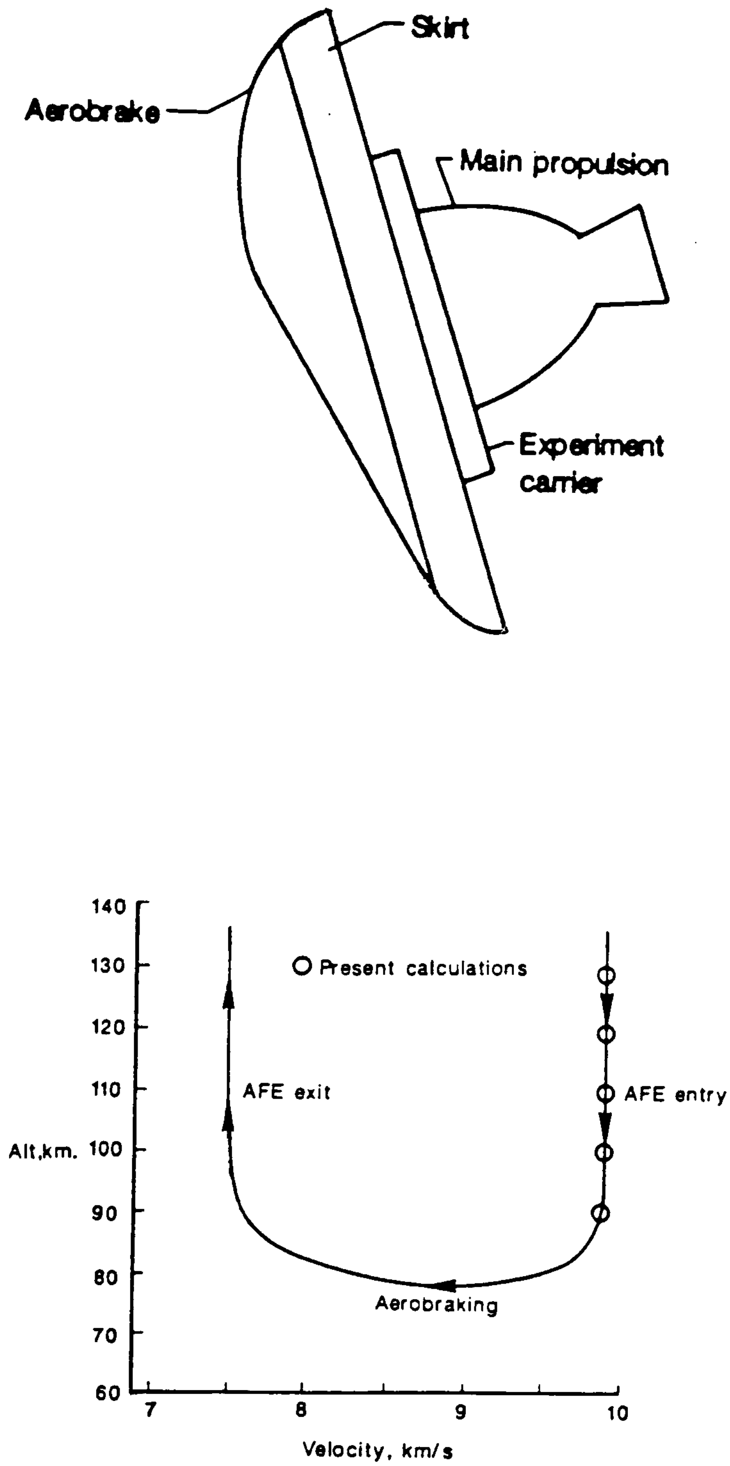

Figure 2. Aeroassist Flight Experiment (AFE) vehicle shape and trajectory (from Reference 8).

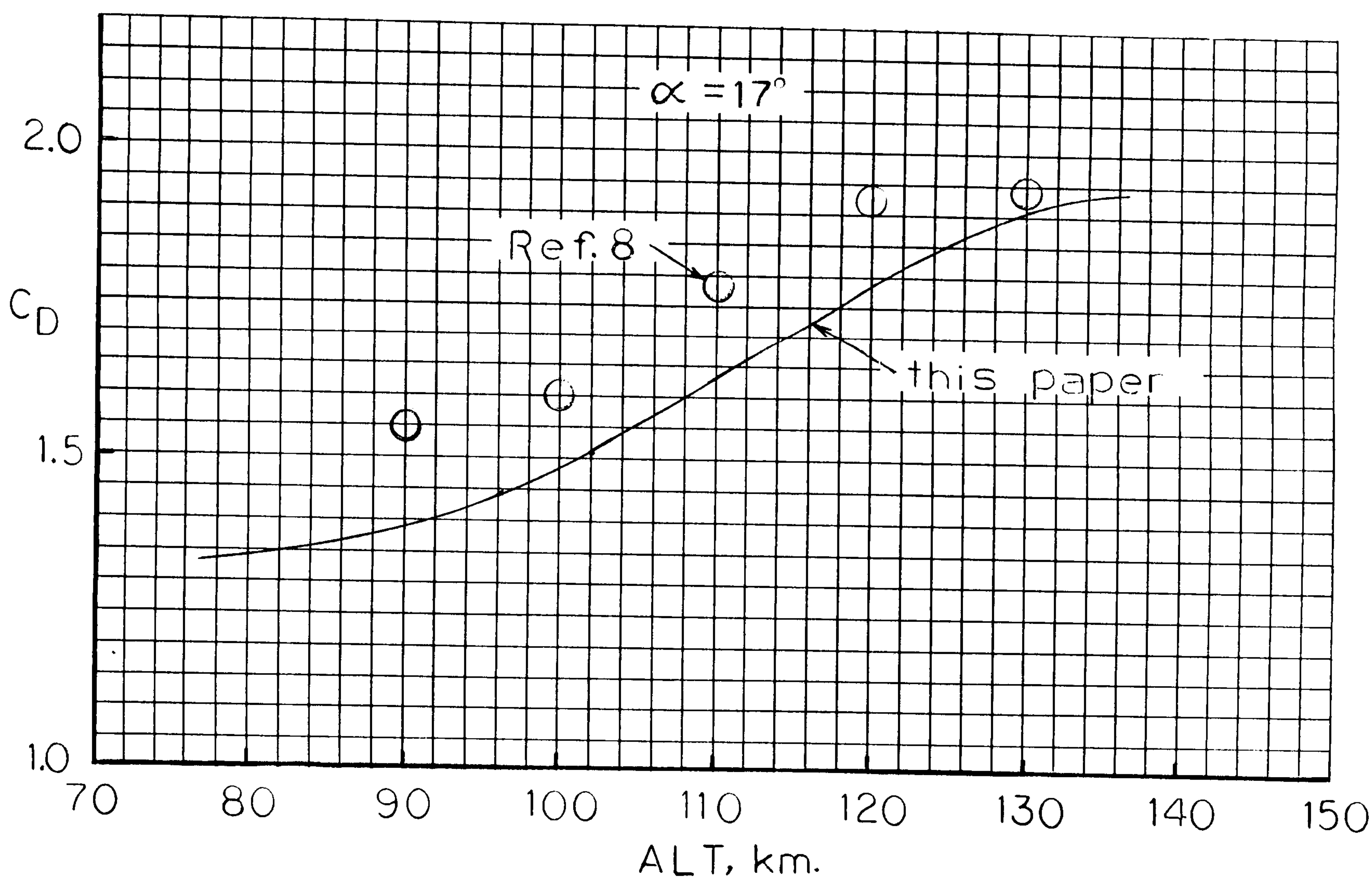

Figure 3. Drag coefficients predicted for the AFE during re-entry.

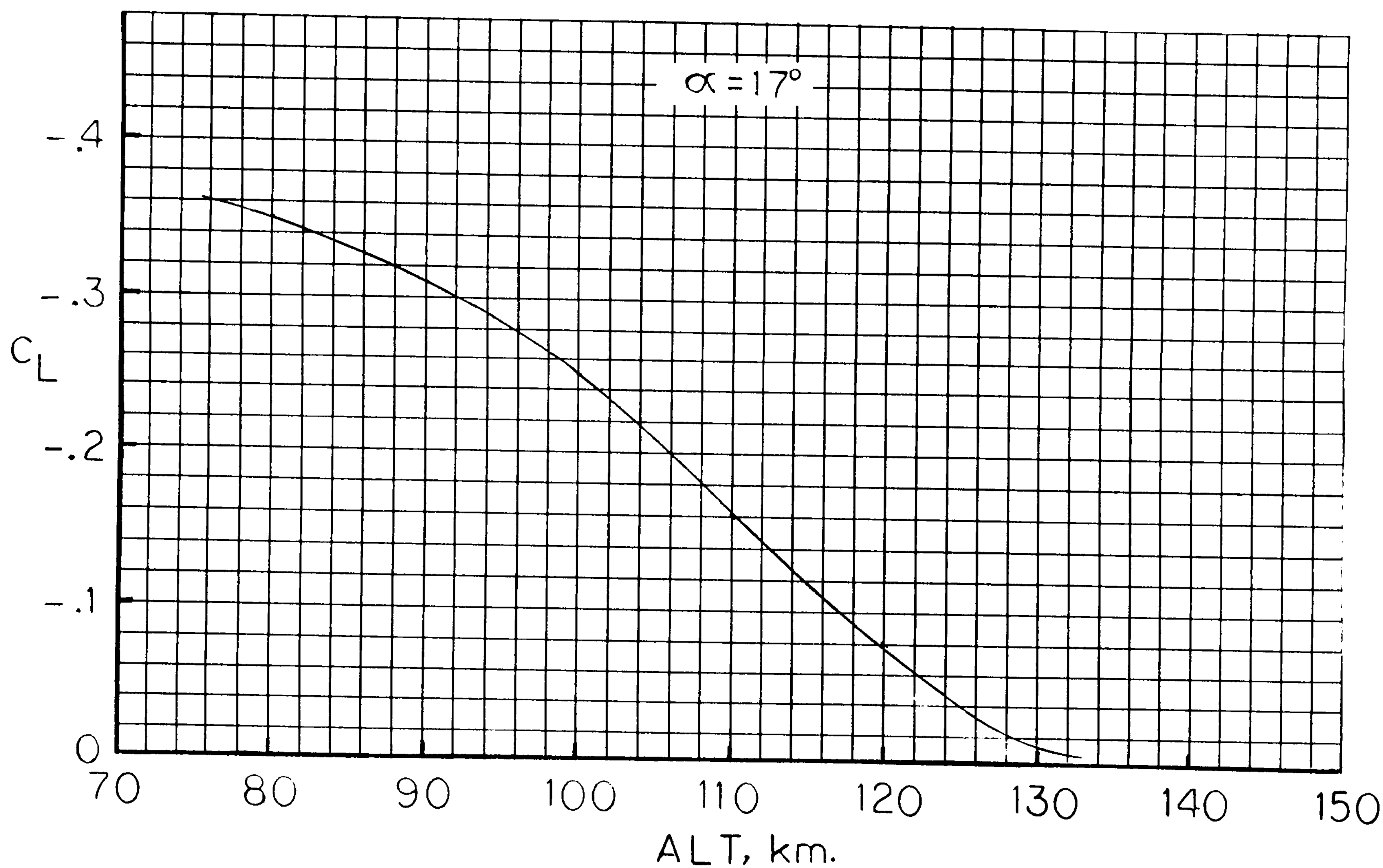

Figure 4. Lift coefficients predicted for the AFE during re-entry.

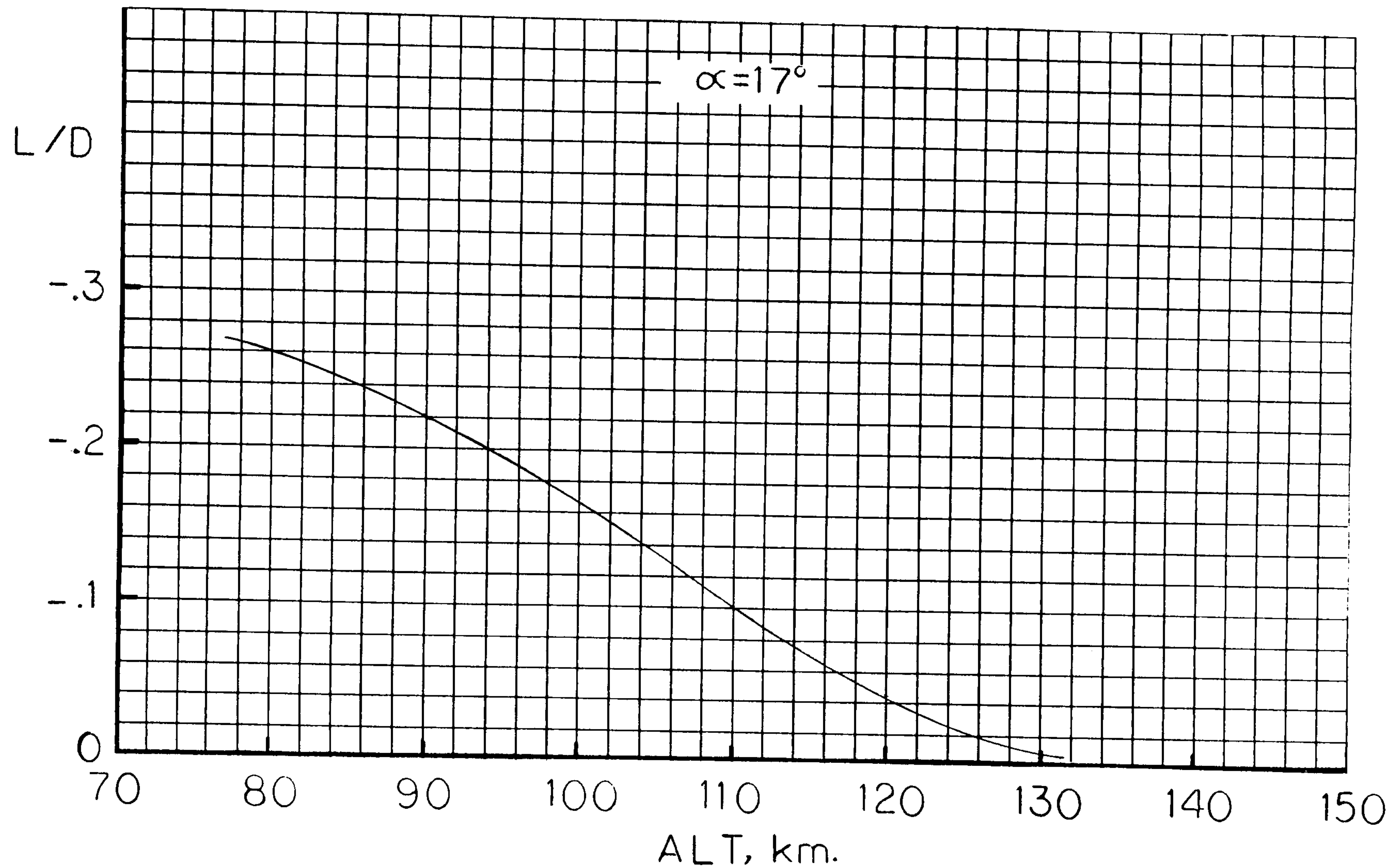

Figure 5. Lift-to-drag ratios predicted for the AFE during re-entry.