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RESEARCH MEMORANDUM

ANALYSIS OF SOME PARAMETERS USED IN CORRELATING BLOWING-TYPE BOUNDARY-LAYER CONTROL DATA

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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ANALYSIS OF SOME PARAMETERS USED IN CORRELATING BLOWING-TYPE BOUNDARY-LAYER CONTROL DATA

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SUMMARY

An examination has been made of limitations to the use of the jet momentum coefficient as a correlating factor in comparing tests of blowing-type boundary-layer control. A theoretical analysis indicates that this parameter should be acceptable where the duct pressures are large. At low pressures, when the jet velocity is of the order of the local stream velocity, the correlating parameter should include a term involving the flow quantity and ratio of the local velocity at the nozzle to the free-stream velocity. Experimental data are shown to substantiate this conclusion.

INTRODUCTION

Experimental results of blowing-type boundary-layer control investigations are often presented as a function of the jet momentum coefficient which is proportional to the product of the mass flow and the velocity of the jet. The choice and use of this parameter have been based on a limited amount of experimental data (refs. 1 and 2, for example) and on physical reasoning. (It would be inferred from consideration of mixing and injector processes that the jet momentum would be one of the most significant parameters.) The results of the investigations reported in references 1 and 2 indicate that, for a given geometrical configuration, a given value of momentum coefficient will enable a given amount of boundary-layer control to be realized, regardless of the particular combination of mass flow and jet velocity chosen to obtain this momentum.

This concept is of considerable importance since it enables a much wider application to be made of any one group of experimental results. Thus a designer considering the use of this form of boundary-layer control need only find data applicable to his particular geometrical configuration, from which he can then compute the required values of mass flow and jet velocity consistent with his particular pumping system.

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While the data presented in references 1 and 2 indicated very good correlation with the momentum coefficient as a parameter, this result has by no means been obtained in all other experimental investigations (e.g., ref. 3). These results, together with a general uneasiness over the frequent use of the momentum coefficient concept to extrapolate wind-tunnel data to combinations of mass flow and jet velocity outside of the range covered by the experimental investigations, prompted a more detailed analysis of the problem. It is the purpose of this paper to present this analysis and the conclusions drawn therefrom.

It is emphasized that no attempt is made here to predict in a quantitative manner the effects of blowing jets into the boundary layer. In particular, no attempt is made to predict the combinations of mass flow and jet velocity required to prevent flow separation on a particular configuration. Instead, this analysis consists only of the derivation of the momentum integral equation describing the flow of the boundary layer over a surface containing a blowing slot, and of an examination of the terms of this equation in an attempt to select a parameter which will satisfactorily correlate the experimental data.

NOTATION

A	area, sq ft
A_j	jet area, sq ft
c	characteristic length of wing chord, ft
C_{BLC}	blowing boundary-layer control parameter, $\frac{h_j}{c}(P_j - P) + 2C_Q\left(\frac{u_j}{U_\infty} - \frac{U}{U_\infty}\right)$
C_L	lift coefficient
C_Q	flow coefficient, $\frac{W}{\rho_\infty g U_\infty c} = \frac{\rho_j u_j h_j}{\rho_\infty U_\infty c}$
C_μ	momentum coefficient, $2C_Q \frac{V_j}{U_\infty}$
g	acceleration of gravity, 32.2 ft/sec^2
h_j	height of nozzle opening, ft

p	static pressure near jet nozzle, lb/sq ft
p_d	total pressure of air in blowing nozzle, lb/sq ft
p_j	static pressure of air jet at nozzle exit, lb/sq ft
p_∞	free-stream static pressure, lb/sq ft
P_d	duct pressure coefficient, $\frac{p_d - p_\infty}{q_\infty}$
P	local wing surface pressure coefficient, $\frac{p - p_\infty}{q_\infty}$
P_j	jet pressure coefficient, $\frac{p_j - p_\infty}{q_\infty}$
q_∞	free-stream dynamic pressure, lb/sq ft
R	gas constant for air, 1715 $ft^2/sec^2\ {}^\circ R$
T_d	total temperature of air in jet nozzle, $^\circ R$
u	velocity of air in boundary layer, ft/sec
u_j	velocity of air at exit of jet nozzle, ft/sec
U	average velocity of air at outer edge of boundary layer near blowing nozzle, ft/sec
U_∞	free-stream velocity, ft/sec
v_h	average vertical component of velocity at $y = h$, ft/sec
V_j	jet velocity assuming isentropic expansion to free-stream pressure, ft/sec
V_N	component of velocity normal to control surface, ft/sec
W	weight rate of flow of air through blowing nozzle, lb/sec
α	angle of attack, deg
γ	ratio of specific heats, 1.4 for air
δ	boundary-layer thickness, ft
ρ_j	density of air at exit of jet nozzle, slugs/cu ft

ρ_∞ free-stream density, slugs/cu ft

τ skin friction per unit area, lb/sq ft

THEORETICAL ANALYSIS

The momentum integral equation for the boundary layer flowing over a surface containing a blowing slot may be derived by equating the pressure and skin-friction forces acting on the boundary layer to the change in momentum of the air in the boundary layer. In the control surface shown in figure 1, the pressure and skin friction forces are given by

$$\begin{aligned} F_x &= p_j h_j + ph - (p + \Delta p)(h + h_j) - \tau\,\Delta x \\ &= h_j(p_j - p) - \Delta p(h + h_j) - \tau\,\Delta x \end{aligned} \qquad (1)$$

If it is assumed that the term $\Delta p(h + h_j)$ is approximately equal to $\Delta p(h)$, then

$$F_x = h_j(p_j - p) - \Delta p h - \tau\,\Delta x \qquad (2)$$

The rate of change of momentum flowing across the control surface is

$$\oint_{ABCD} \rho u V_N dA = -\int_0^h \rho u^2 dy + (\rho v_h \Delta x)U \cos\varphi + \int_{-h_j}^h \rho u^2 dy - \rho_j u_j^2 h_j$$

$$= \Delta\int_{wall}^h \rho u^2 dy + \rho v_h U \Delta x - \rho_j u_j^2 h_j \qquad (3)$$

where $\int_{wall}^h$ denotes integration from the surface out to h, and the angle φ has been assumed to be small so that $\cos\varphi \approx 1.0$. The vertical component of velocity, v_h, of the fluid leaving the upper boundary of the control surface may be evaluated by the condition of continuity

$$\left.\begin{aligned} \oint_{ABCD} \rho V_N dA &= -\int_{0}^{h} \rho u\, dy + \rho v_h \Delta x + \int_{-h_j}^{h} \rho u\, dy - \rho_j u_j h_j = 0 \\ \rho v_h \Delta x &= \rho_j u_j h_j - \Delta \int_{\text{wall}}^{h} \rho u\, dy \end{aligned}\right\} \qquad (4)$$

With the above expression for $\rho v_h \Delta x$ equation (3) becomes

$$\oint_{ABCD} \rho u V_N dA = \Delta \int_{\text{wall}}^{h} \rho u^2 dy - U\Delta \int_{\text{wall}}^{h} \rho u\, dy + \rho_j u_j h_j (U - u_j) \qquad (5)$$

Since the change in momentum of the fluid flowing across the control surface must equal the net force impressed on the control surface

$$\left.\begin{aligned} F_x &= \oint_{ABCD} \rho u V_N dA \\ h_j(p_j - p) - \Delta p h - \tau \Delta x &= \Delta \int_{\text{wall}}^{h} \rho u^2 dy - U\Delta \int_{\text{wall}}^{h} \rho u\, dy + \rho_j u_j h_j (U - u_j) \end{aligned}\right\} \qquad (6)$$

If equation (6) is made dimensionless by dividing through by $\frac{1}{2} \rho_\infty {U_\infty}^2 c$, the result is

$$2\Delta \int_{\text{wall}}^{h} \frac{\rho}{\rho_\infty} \left(\frac{u}{U_\infty}\right)^2 d\left(\frac{y}{c}\right) = 2\,\frac{U}{U_\infty}\,\Delta \int_{\text{wall}}^{h} \frac{\rho}{\rho_\infty}\,\frac{u}{U_\infty}\, d\left(\frac{y}{c}\right) - \frac{h}{c}\,\Delta P - \frac{\tau}{q_\infty}\,\Delta\left(\frac{x}{c}\right) +$$

$$\frac{h_j}{c}\,(P_j - P) + 2C_Q\,\frac{u_j}{U_\infty} - 2C_Q\,\frac{U}{U_\infty} \qquad (7)$$

This equation relates the change in momentum of the fluid flowing across the control surfaces upstream and downstream of the slot to the momentum lost through the upper control surface, the external pressure gradient, the skin friction, and the characteristics of the jet. The above equation indicates that two blowing boundary-layer control systems will have an equivalent effect on the momentum only if the sum of the terms on the right-hand side of equation (7) is held constant. The sum of the terms

$$\frac{h_j}{c}\left(P_j - P\right) + 2C_Q \frac{u_j}{U_\infty}$$

represents the momentum of the jet in dimensionless form, and, as will be shown later, is approximately equal to C_μ. The term, $-2C_Q(U/U_\infty)$, represents the momentum lost through the upper control surface due to the jet flow into the lower control surface as indicated by equations (4) and (5). The influence of the jet on the terms involving the change in mass of fluid flowing across the upstream and downstream control surfaces, the external pressure gradient, and the skin friction, is unknown and depends upon a knowledge of the distribution of turbulent shearing stresses across the boundary layer, and on the relation between these stresses and the mean velocity profiles. Since a continuation of the analysis to develop these relationships would be a formidable task, it is assumed that, to a first approximation, the influence of changes in the jet on these terms can be neglected for the type of changes in the jet characteristics being considered. Within the limits of these restrictions and assumptions, then, the parameter C_{BLC} defined as

$$C_{BLC} = \frac{h_j}{c}\left(P_j - P\right) + 2C_Q\left(\frac{u_j}{U_\infty} - \frac{U}{U_\infty}\right) \tag{8}$$

should specify the characteristics of two different jets which will impart equal momentum to the boundary layer and, presumably, will provide identical boundary-layer control effectiveness for similar geometric arrangements. Specifically, if the boundary-layer control effectiveness of a particular jet having a given mass flow and velocity has been experimentally determined, the parameter, C_{BLC}, should describe other combinations of mass flow and velocity giving the same degree of boundary-layer control. This will be investigated empirically in a later section of the report.

For the subsonic jet velocities, $P_j = P$, and the above expression reduces to

$$C_{BLC} = 2C_Q \frac{u_j}{U_\infty} - 2C_Q \frac{U}{U_\infty} \tag{9}$$

The momentum coefficient is customarily defined by

$$C_\mu = 2C_Q \frac{V_j}{U_\infty} \tag{10}$$

where V_j has, for convenience only, been arbitrarily assumed to be the jet velocity resulting from isentropic expansion from the total pressure in the duct ahead of the blowing nozzle to free-stream static pressure rather than local static pressure. With this definition of C_μ, equation (9) can be written

$$C_{BLC} = C_\mu \sqrt{1 - \frac{P}{P_d}} - 2C_Q \frac{U}{U_\infty} \tag{11}$$

if incompressible flow through the nozzle is assumed. If the actual jet velocity, u_j, is approximately equal to V_j, then the factor $\sqrt{1 - P/P_d}$ in equation (11) approaches 1.0 and this equation can be approximated by

$$C_{BLC} \approx C_\mu - 2C_Q(U/U_\infty) \tag{12}$$

For the case of a simple convergent blowing nozzle operating at supercritical pressure ratios, it can be shown that the jet velocity obtained by the nonisentropic free jet expansion is

$$V_{ex} = u_j + \frac{p_j - p}{\rho_j u_j} \tag{13}$$

if mixing losses at the jet boundary are ignored. Further, it can be shown that for the pressure ratio range of practical interest, the jet velocity computed from equation (13) is nearly equal to that which would be obtained from isentropic flow relationships, the difference being about 8 percent at a pressure ratio of 10. If V_j can be approximated by V_{ex}, then

$$C_\mu = 2C_Q \frac{V_j}{U_\infty} \approx 2C_Q \frac{V_{ex}}{U_\infty} \approx 2C_Q \frac{u_j}{U_\infty} + \frac{h_j}{c} (P_j - P) \tag{14}$$

If the above relationship is substituted in equation (8) then the boundary-layer control parameter, C_{BLC}, for supersonic jet velocities is approximately given by

$$C_{BLC} \approx C_\mu - 2C_Q \frac{U}{U_\infty} \tag{15}$$

which is the same as given by equation (12) for subsonic jets.

SUMMARY OF RESULTS OF ANALYSIS

The main result indicated by this analysis is that the parameter, C_μ, alone is not sufficient to specify entirely the effects of blowing on the momentum of the boundary layer. The effects of blowing are more adequately described by the parameter, C_{BLC}, defined by

$$C_{BLC} = \frac{h_j}{c}(P_j - P) + 2C_Q\left(\frac{u_j}{U_\infty} - \frac{U}{U_\infty}\right)$$

If the actual jet velocity, u_j, is approximately equal to that which would be computed for an isentropic expansion from the duct total pressure to free-stream static pressure, then C_{BLC} can be expressed by

$$C_{BLC} \approx C_\mu - 2C_Q \frac{U}{U_\infty}$$

This result indicates that the momentum coefficient will correlate blowing-type boundary-layer control results only to the extent that changes in the quantity $2C_Q(U/U_\infty)$ can be neglected.

The practical significance of this result is indicated in figure 2, which shows the C_μ required for a constant value of C_{BLC} of 0.03 as a function of duct pressure coefficient, P_d. (While these curves were computed assuming incompressible flow through the blowing nozzle, they are at least qualitatively correct for systems for which the assumption of incompressible flow in the nozzle cannot be made.)

Figure 2 indicates that, for blowing boundary-layer control systems which utilize relatively high-pressure air, the same correlation would be obtained with either C_{BLC} or C_μ. However, for low-pressure blowing, this is no longer true.

COMPARISON WITH EXPERIMENT

In order to check the boundary-layer control parameter suggested by the theoretical analysis, data from the investigation of reference 4 have been used. These particular data were chosen because relatively low-pressure air (maximum $P_d = 12$) was used for the boundary-layer control system, and, hence, discernible differences should exist between correlations based on C_μ and C_{BLC}. Further, a sufficient number of nozzle sizes were tested (and therefore sufficient combinations of mass flow and jet velocity were available) to demonstrate whether these differences did, in fact, exist.

Figure 3 shows the variation of C_L at $\alpha = 0^\circ$ with C_μ for various nozzle sizes with the nozzle exit at 53.9-percent chord. It is seen that the initial effect of blowing was to cause a loss in lift. This would be expected since the theoretical analysis indicates that blowing would decrease the boundary-layer momentum unless the jet velocity exceeded the local velocity outside of the boundary layer. The variation of C_L with u_j/U_∞, shown in figure 4, indicates that the detrimental effects of blowing are restricted to values of u_j/U_∞ below 1.2 to 1.4. A value of U/U_∞ of about 1.3 would appear reasonable at the location of the slot on this airfoil at 0° angle of attack, so it would appear that the detrimental effects of blowing are restricted to values of u_j/U less than 1.0. However, it should be noted that the data presented in figure 4 indicate that the value of u_j/U_∞ required to nullify the initial loss in lift due to blowing depends, to some extent, on the size of the nozzle opening; that is, the value of u_j/U_∞ required to obtain the same C_L as was obtained with no blowing varied from about 1.2 for $h_j/c = 0.00667$ to about 1.4 for $h_j/c = 0.00167$. Variations of the same magnitude or greater were found in the data presented in reference 4 for configurations having the nozzle at other chordwise positions. There is not sufficient information available to determine whether this variation is due to the experimental technique used or to effects which were assumed negligible in the analysis (such as changes in the local pressure coefficients and skin friction with changes in nozzle opening).

The variation of C_L with C_{BLC} is presented in figure 5, with C_{BLC} evaluated by equation (8) and with U/U_∞ assumed equal to 1.3. The degree of correlation demonstrated in figure 5 was not obtained for all of the configurations tested in the investigation reported in reference 4, due, primarily, to the apparent variation with nozzle size of the value of u_j/U_∞ required to nullify the initial loss in lift due to blowing, as previously discussed. However, the experimental data appear to verify at least partially the theoretical conclusion that, for low-pressure blowing boundary-layer control systems, the parameter C_μ may not adequately correlate the effects of blowing on the boundary layer.

A further check on the conclusions obtained from the theoretical analysis may be obtained by utilizing the data of reference 1 for a wing employing high-pressure blowing over a trailing-edge flap. The variation of C_L with C_μ obtained from this investigation is shown in figure 6. It is seen that good correlation with C_μ was obtained. This result is in agreement with the theoretical analysis which indicated that for high-pressure blowing systems such as that used in the investigation of reference 1, reasonably good correlation with momentum coefficient should be obtained. The variation of lift coefficient with the parameter C_{BLC} is shown in figure 7, and it is seen that good correlation is also obtained using this parameter.

A final point worthy of note concerns the choice between subsonic and supersonic jets for blowing boundary-layer control systems. There have been a considerable number of statements made inferring the superiority (with respect to momentum coefficient requirements) of blowing systems using supersonic jets over those employing subsonic jets. However, experimental results show no particular significance associated with the attainment of sonic velocity by the jet. This is demonstrated quite well in figure 6, where the C_μ values at which the blowing jet reaches sonic speed are indicated. It can be seen that, in the C_μ range from 0.04 to 0.08 the smaller jet ($h/c = 0.00036$) is supersonic, while the larger jet ($h/c = 0.00072$) is subsonic, yet no discernible difference in the effectiveness of the boundary-layer control is evident.[1]

CONCLUSIONS

The following conclusions are drawn from the theoretical analysis and experimental data presented in this report.

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[1] A second reason which has been given for the use of supersonic blowing is that this automatically insures a uniform spanwise distribution of blowing, since the nozzle is choked. This is not strictly correct. The weight rate of flow which can be driven through a choked nozzle is given by the equation

$$W = gp_d\sqrt{\frac{\gamma}{RT_d}}\left(\frac{\rho}{\rho_d}\right)^*\left(\frac{a}{a_d}\right)^* A_j$$

where $(\rho/\rho_d)^* = 0.6339$ and $(a/a_d)^* = 0.9129$ for air flow in choked nozzles. This equation shows that uniform spanwise distribution of blowing from a choked nozzle can be obtained only when there is no significant spanwise variation of duct pressure. The real criterion that must be satisfied, if a reasonably uniform spanwise distribution of blowing is to be obtained, is that the spanwise duct pressure drop must be small compared to the pressure drop across the blowing nozzle. As long as this condition is satisfied, the spanwise variation of blowing will be small regardless of whether or not the nozzle is choked.

1. The increase in momentum due to blowing a jet of air into the boundary layer is more adequately described by the product of the mass flow of the jet and the difference between the jet velocity and the local stream velocity than it is by the jet momentum.

2. For most of the high-pressure blowing boundary-layer control systems of current practical interest, variations in the local stream velocity are small relative to the jet velocity and, therefore, good correlation of results with jet momentum should be obtained.

3. For very low-pressure blowing boundary-layer control systems where the jet velocity is of the order of the local stream velocity good correlation of results with jet momentum may not be obtained.

4. Both theory and experiment indicate that, if the jet velocity is less than the local stream velocity over the airfoil near the nozzle, the effects of blowing will be to reduce the boundary-layer momentum and presumably will be destabilizing rather than stabilizing.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., June 12, 1956

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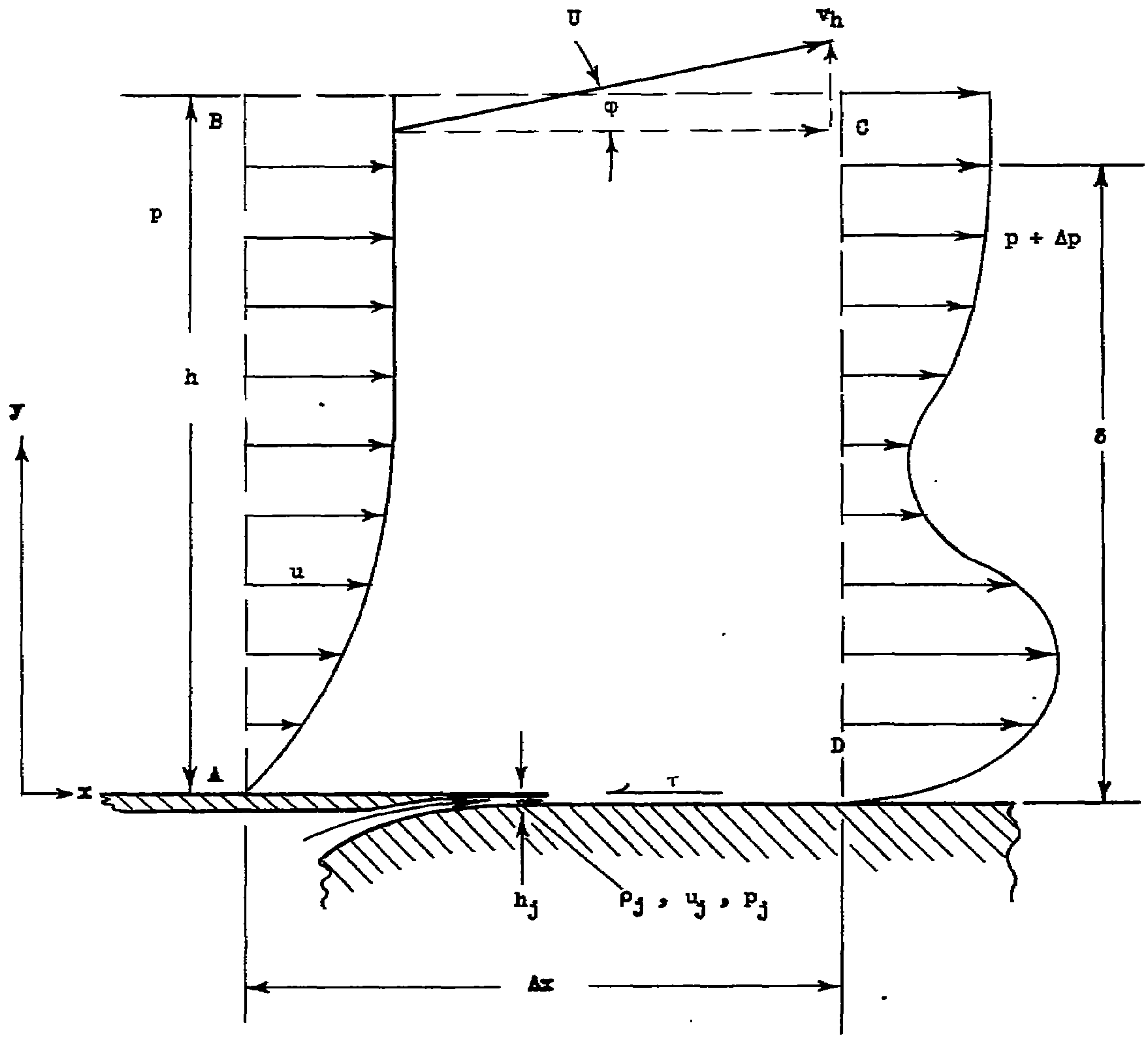

Figure 1.- Control surface used for theoretical development.

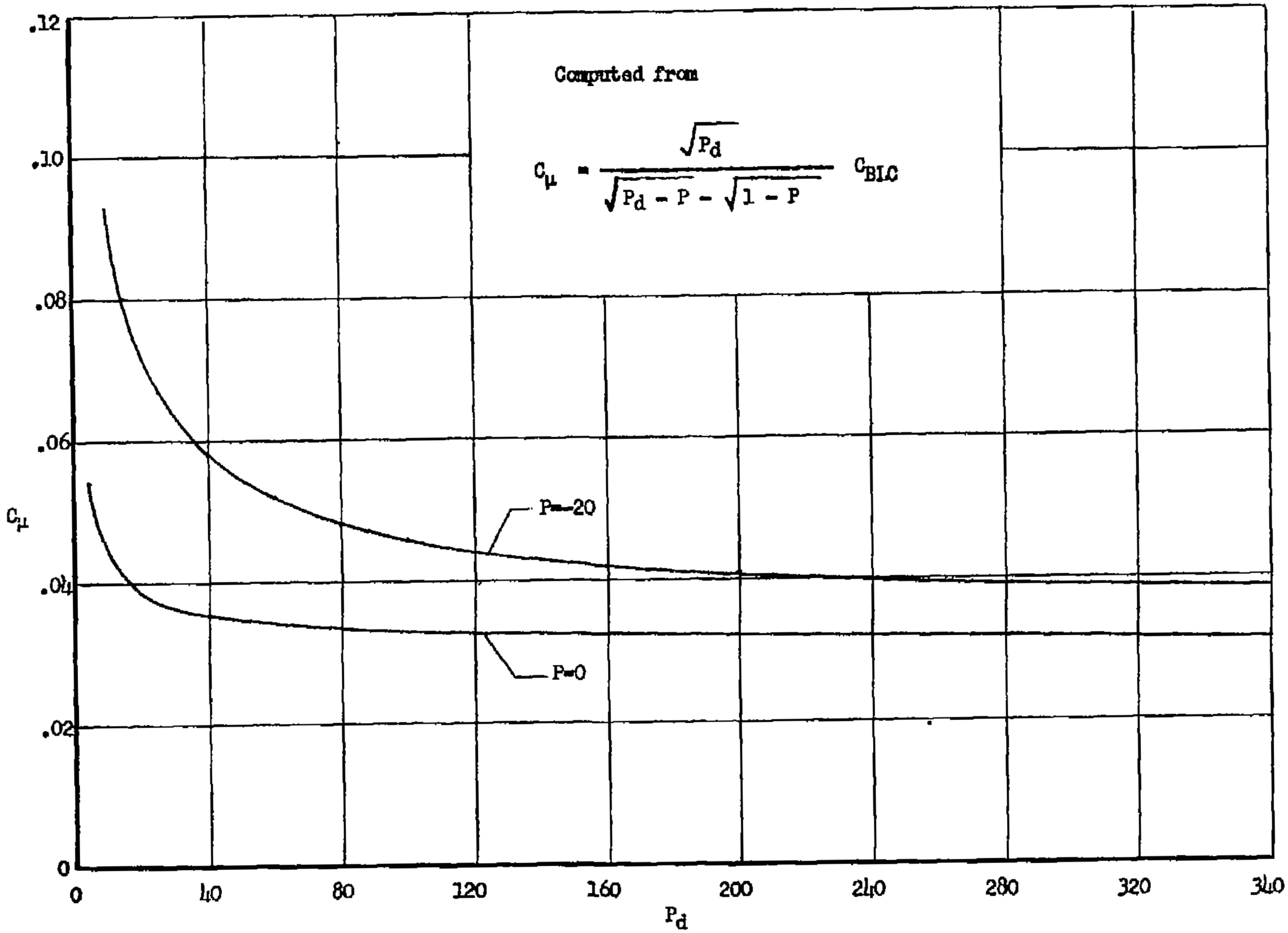

Figure 2.- Variation of C_μ with P_d for a constant value of C_{BLC}.

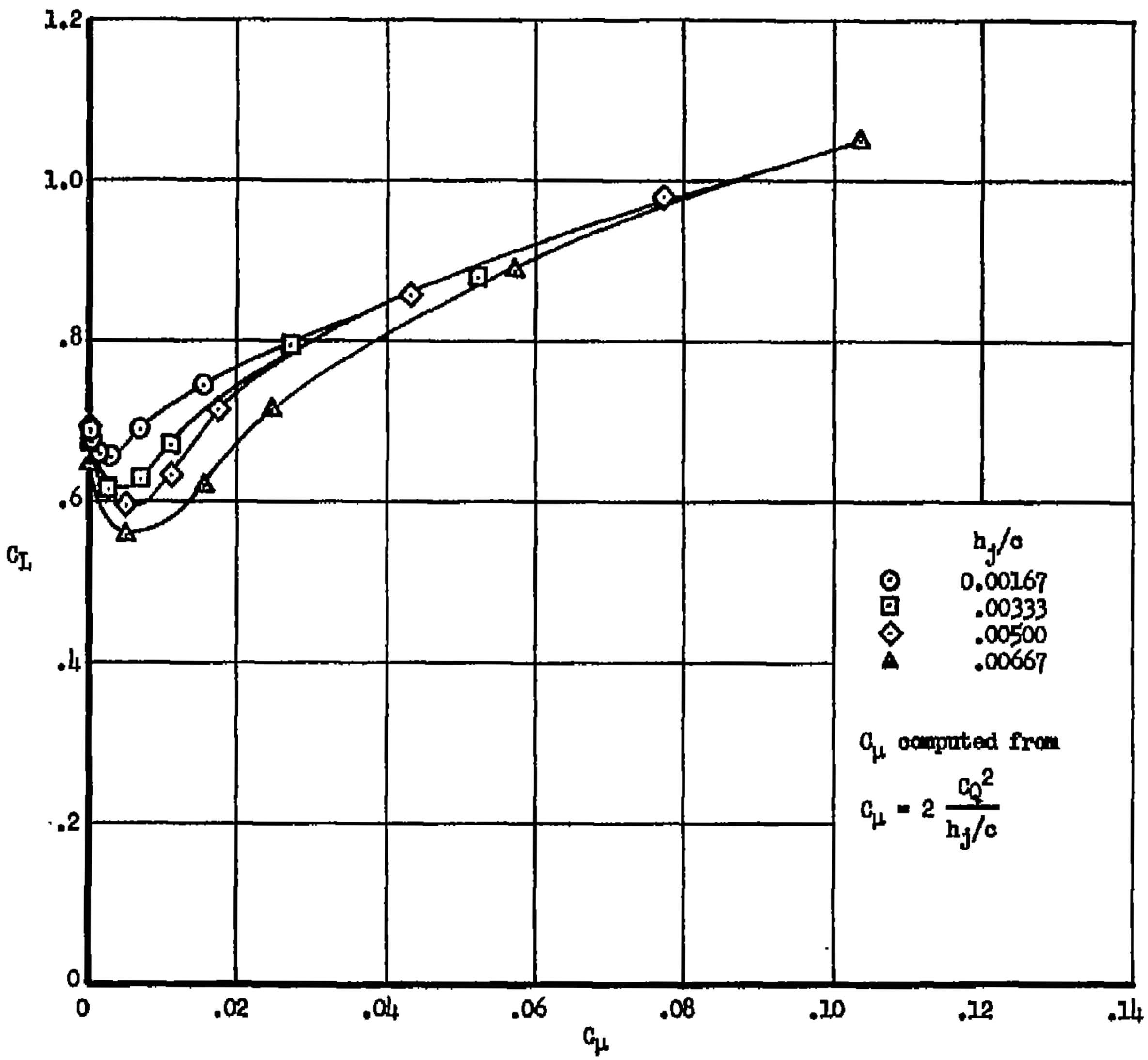

Figure 3.- Variation of C_L with C_μ data from reference 4.

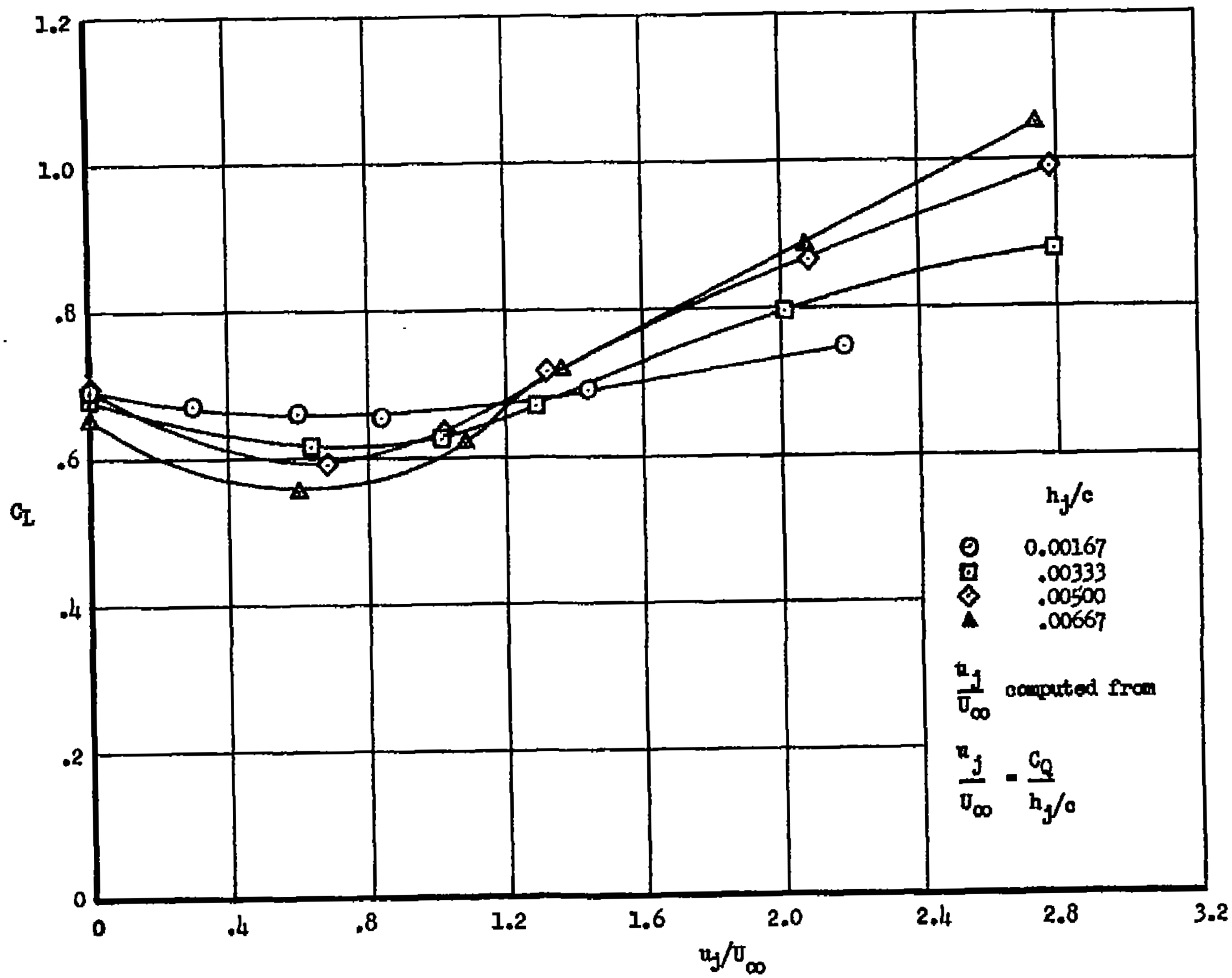

Figure 4.- Variation of C_L with u_j/U_∞ data from reference 4.

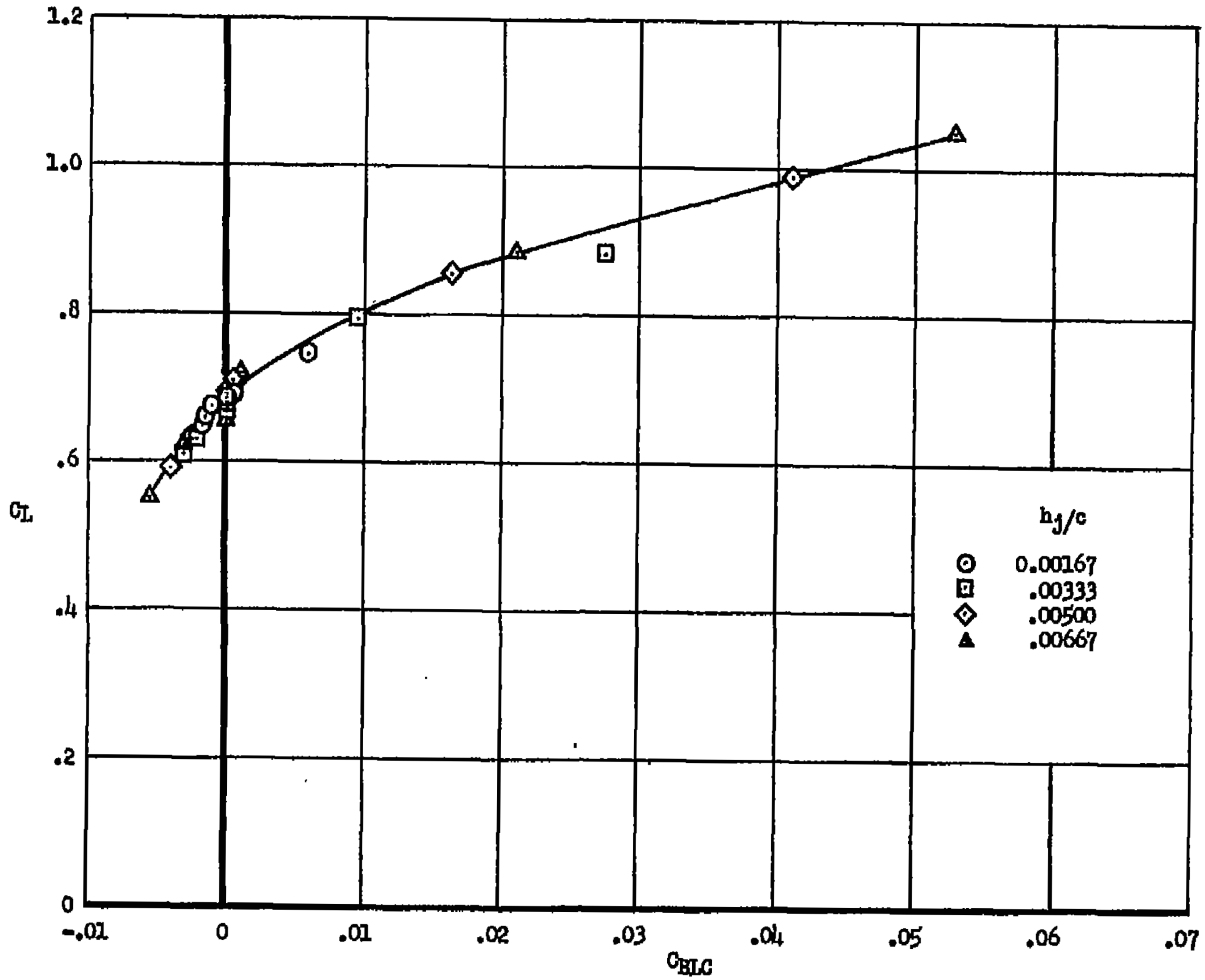

Figure 5.- Variation of C_L with C_{BLC} data from reference 4.

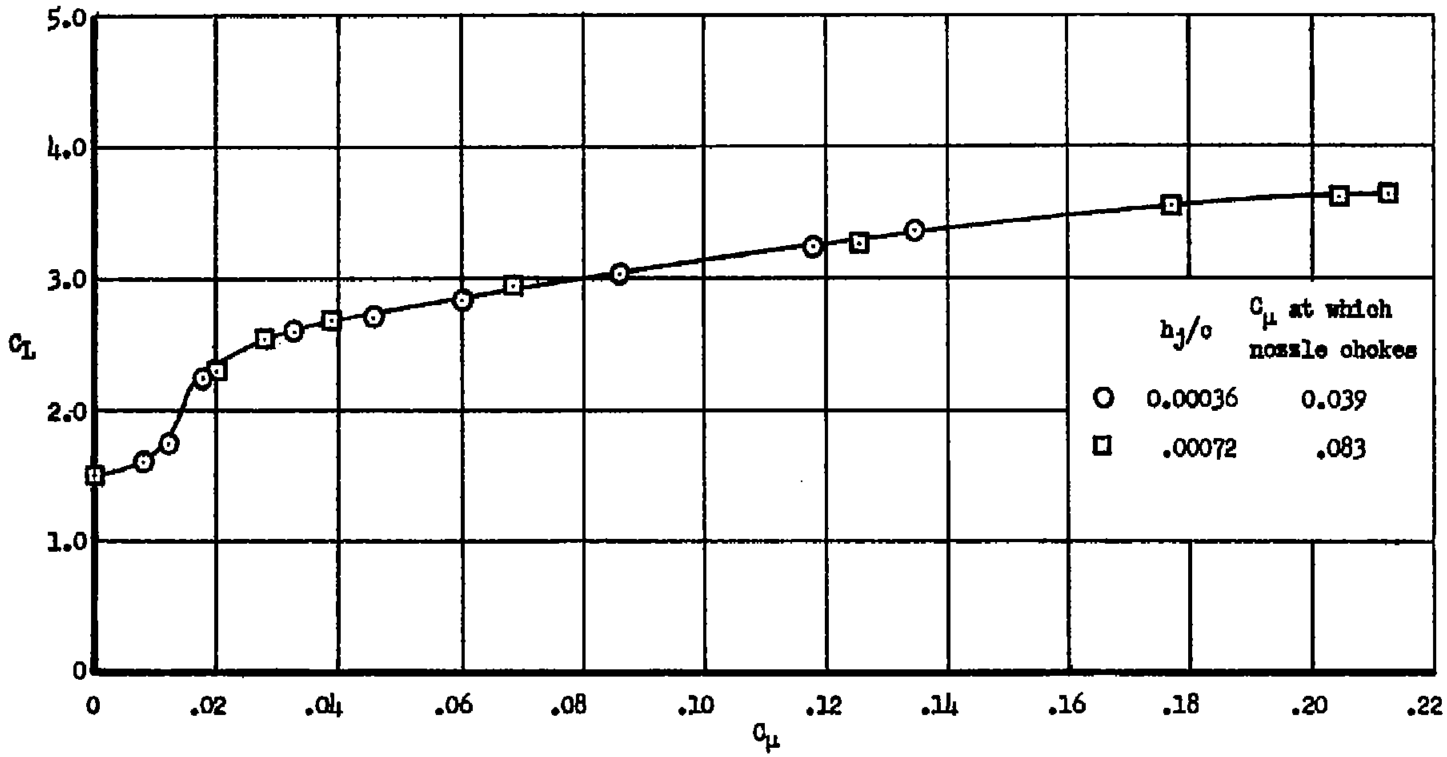

Figure 6.- Variation of C_L with C_μ data from reference 1.

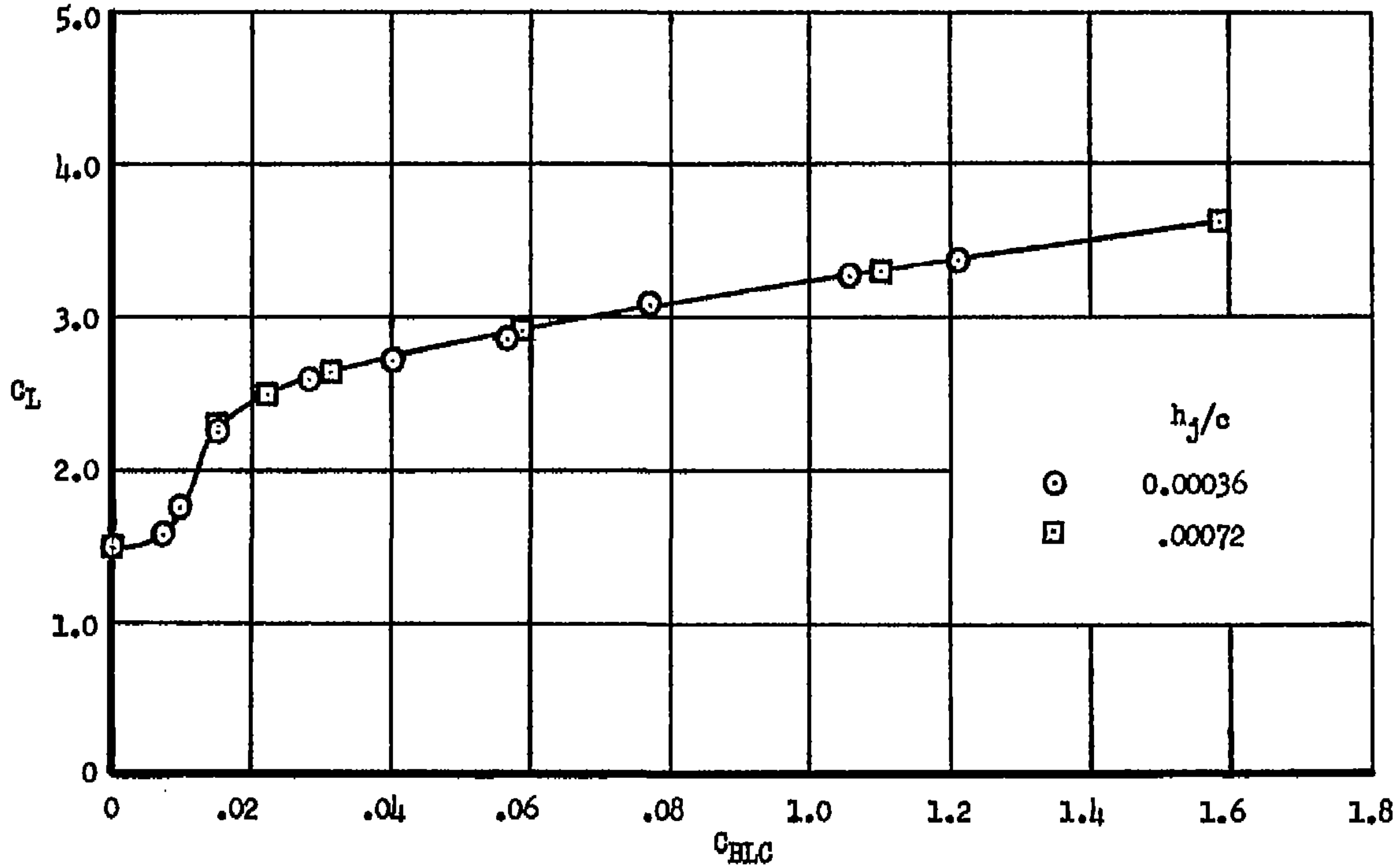

Figure 7.- Variation of C_L with C_{BLC} data from reference 1.

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