

OPTIMUM SUCTION ON A POWER BASIS

By

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CHAPTER I

INTRODUCTION

One of the most critical problems facing the aircraft industry today has been the problem of reducing the high landing and take-off speeds of modern day military and commercial aircraft without sacrificing high cruising speeds and high altitude performance. Lower landing speeds would mean an increase in safety in the landing phase of flight and a decrease in the cost of operation. Safety, in that a man would have more time to apply a correction for errors in flight path and the aircraft would have more time to respond to the correction. The cost of operation would be decreased, in one respect, by a considerable saving in the requirement for a continued program in designing a complex and expensive braking system. With lower speeds, wear of brakes and gear would also be reduced. Too, the necessity of having to extend existing runways, or having to move to new locations when there is not enough land available to accomodate high speed aircraft would be alleviated.

Of course, aeronautical engineers the world over have been striving to obtain the optimum airplane. Militarily, this would be an aircraft that would meet all the requirements with as small a gross weight as possible. Commercially, it would be an aircraft designed for minimum operating cost. (Perkins, page 206). There have been many advances made towards the realization of such an aircraft. One of the many methods

that have been employed to obtain better performance of an aircraft has been that of reducing its total drag. That is, with less drag, there would be a proportionately less amount of thrust required, thus resulting in an increase in performance.

The drag of an airplane consists of the induced drag, frictional drag, and the form or pressure drag of its wing, fuselage, tail unit, and other prominent components. Investigations have shown the frictional drag to be the main portion of the total drag. Hence, the reduction of surface friction has been of considerable importance. (Pfenninger, page 1). Large reductions in frictional drag have been obtained by boundary-layer-control using area suction. (Schlichting, page 229). However, in proposing a method of boundary-layer-control by area suction, the greatest objection has been to the added weight required for the suction equipment and ducting. So that even though performance was increased, the payload and range were reduced because of the added equipment required for suction. Also, the power used in suction to decrease the drag might be used more advantageously in the output of the engine in obtaining a better performing aircraft.

If a point could be found, such that the benefit derived from the total drag reduction by area suction would just balance the power requirements for boundary-layer-control, then perhaps a system based on a condition of this nature might be economically acceptable to the aircraft industry. If such a condition could be found to exist, then not only could better performance be obtained, resulting in lower approach, landing and take-off speeds; but, the saving in weight would allow for

an increase in payload or an increase in range which would increase the over-all performance of the aircraft.

This was the objective of this paper; namely, the investigation of the possibility of an equilibrium point existing between the power required for boundary-layer-control, using area suction, and the drag reduced; such that, the power expended would be a minimum. If an equilibrium point described existed, and a satisfactory increase in performance could still be realized, then we would be one step closer to the solution to one of the aircraft industry's most pressing problems which has been that of trying to optimize the performance of an aircraft in as many phases of flight as possible without making extreme compromises in different regimes of flight.

CHAPTER II

PREVIOUS INVESTIGATIONS

The first fundamental investigation of boundary-layer-control by suction was performed by L. Prandtl in the early part of the twentieth century, only forty-six years ago. His results, performed on a circular cylinder, showed that the flow was influenced by the suction and that the flow adhered to the cylinder for a greater distance along the surface in the direction of flow. (Schlichting, page 36). Then in 1928 the assumption was first expressed by B. M. Jones that a laminar boundary-layer might possibly be maintained for a longer distance over an airfoil with boundary-layer suction which would reduce the drag due to friction on the airfoil. (Pfenninger, page 28). Later, L. Prandtl calculated the laminar boundary-layer with suction for a pressure increase.

Since those first investigations, the results from both theoretical and experimental investigations have shown conclusively that a sizeable reduction in drag can be obtained by controlling the structure and the growth of the boundary-layer on a wing by the application of suction. Some of the men that have contributed greatly to a better understanding of this phenomenon, other than Prandtl, are H. Schlichting, W.P. Pfenninger, Th. von Karman, Ackeret, A. Raspet, Iglisch, and Schrenk to mention a few.

In their investigations, they have established the now well-known fact that laminar flow can support only a small adverse pressure gradient,

but a turbulent flow can overcome a much stronger pressure gradient; that is, separation can be shifted further downstream on an airfoil by causing an early transition from laminar to turbulent flow. However, the velocity gradient at the surface in a turbulent flow has been shown to be much greater than that for a laminar flow, thereby causing large changes in the frictional drag with the growth of a turbulent boundary-layer. (Schlichting, page 222).

The position of the transition point, then, greatly influences the amount of friction drag of a body in a flow field. Transition can be made to occur further downstream by a decreased pressure gradient in the direction of flow. This can be accomplished on an airfoil by placing the maximum thickness as far to the rear as possible. A series of airfoils were developed using this concept. They were designated as laminar airfoils. (Schlichting, page 222). Boundary-layer-suction also influences the point of transition and consequently the magnitude of the skin friction by decreasing the displacement thickness of the boundary-layer. (Schlichting, page 311). Theoretically, the point of transition is identical to the point of instability and differs only by the time delay in transition. It has been defined as the point where the critical Reynolds number and the local Reynolds number, based on the displacement thickness of the boundary-layer, are equal. (Schlichting, page 318). The boundary-layer is considered stable when the local Reynolds number is smaller than the critical Reynolds number. (Schlichting, page 342).

Another method that has been used to control the boundary-layer is

that of imparting additional energy into the fluid near the surface. This produces an acceleration of the boundary-layer, and thus reduces the possibility of separation. However, transition was found to occur much earlier which was undesirable since the advantage gained by delaying separation was offset by the increased drag due to the growth of a turbulent boundary-layer. Also, the jets, which were used to eject the addition fluid into the boundary-layer, had to be very small in order to reduce the energy required. With this requirement the jet dissolved into vortices shortly behind the discharge section increasing turbulence. (Schlichting, page 227). For these reasons, it would not seem likely that this method would be used in practice.

Therefore, the method of boundary-layer-control by suction, in conjunction with a laminar airfoil, appears to have the greatest practical importance among all the methods previously investigated. (Schlichting, page 229). Also, in all the previous investigations that the writer has studied in a review of available literature, it has been found that the major emphasis has been placed on obtaining an optimum value of suction flow coefficient that would produce a maximum reduction in drag. The writer has not as yet found information concerning the investigation for a value of suction flow coefficient that not only will produce a benefit in drag reduction, but will result in a minimum expenditure in the power required.

With this and the previous considerations mentioned in mind, the experimental results obtained by Braslow, and colleagues, was deemed an appropriate work for this particular investigation to determine whether

an equilibrium point existed between the suction required and the drag reduced; such that the power expended would be a minimum.

CHAPTER III

EXPERIMENTS PERFORMED ON A LAMINAR AIRFOIL USING AREA SUCTION

A low-turbulence wind tunnel investigation of an NACA 64A010 two-dimensional wing, having a porous surface, was made to determine the maximum reduction in total section drag that could be obtained by the application of area suction. The tests were made at a section angle of attack equal to zero degrees and at body Reynolds numbers, based on a chord length of three feet, which varied from 3×10^6 to 19.8×10^6 . In addition to the experimental investigation a related, brief, theoretical analysis was made to provide a qualitative comparison of the test results. (Braslow).

Description of the Three Configurations Tested

Three different configurations of the NACA airfoil were used as models. The models were constructed with two hollow cast-aluminum end sections and connected to a hollow center under-contoured casting to support a sintered-bronze surface. These sections and skin were contoured to an NACA 64A010 wing profile. Very little of the porous skin was blocked off from the suction flow in the first model, which was designated as configuration one. Configuration two had orifices and sealing rods installed between the skin and the center casting, forming

compartments, which were sealed with rubber cement to prevent flow between compartments. The third configuration had the orifices replaced by a low porosity skin. The flow between compartments in this configuration was not prevented.

Experimental data obtained from the first configuration is presented in Figure 1. (Braslow, page 442). The test results show the variation in total section drag coefficient and the suction drag coefficient with the suction flow coefficient for Reynolds numbers varying from 3×10^6 to 16.7×10^6 . The total section drag coefficient included the power required for suction in the form of the suction drag coefficient which was directly proportional to the suction flow coefficient and the suction pressure coefficient as shown later in this chapter. The suction pressure coefficient (C_p) was assumed to be constant throughout inside the airfoil. There was a considerable reduction in the total drag, even with suction power included, for decreasing values of suction flow coefficient (C_Q) up to the point where an optimum value of C_Q , that gave a maximum reduction in drag, was obtained. This optimum value of C_Q varied for different values of Reynolds number. The region that the writer was primarily interested in lay between this optimum value of C_Q and some lower value of C_Q which would produce an optimum value of suction based on power requirements.

It was believed that excessive amounts of suction air were required at the leading and trailing edges of the porous material, in order to prevent a reversal of flow, that accounted for the suction drag coefficient (C_{ds}) to form a major portion of the total section drag coefficient.

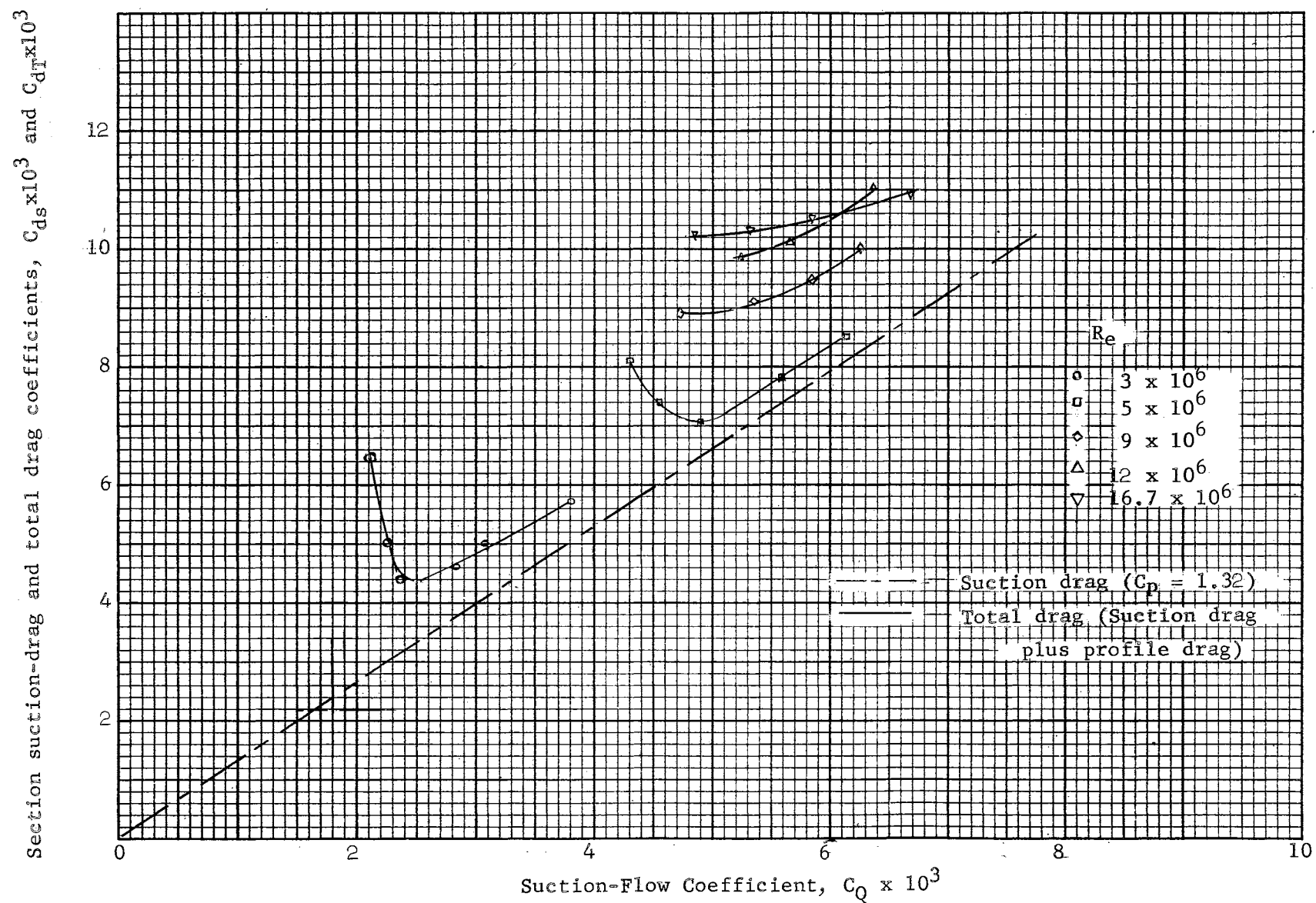


Figure 1. Variation of Section Drag Coefficients With Suction for a Porous Bronze NACA 64A010 Airfoil Model. $C_v/ct = 7.2 \times 10^{-9}$; $\alpha_0 = 0^\circ$; Configuration 1.

In order to reduce this undesirable condition, configuration two was sealed to a point one inch back from the leading edge to obtain drag reductions at reasonable suction flow coefficients. These results are presented in Figure 2 in the manner as for the first configuration. A large improvement in the drag reduction was observed as compared to that of the first configuration. (Braslow, page 445). The third model gave the most significant improvement of all the models tested. The leading edge of the third model was sealed to the five per cent chord position and utilized a skin dense enough to prevent reversal of flow through the skin. The results are shown in Figure 3. (Braslow, page 446).

Determination of Suction Drag Coefficient

If the plumbing system for suction had an efficiency of n_s , the power required would be as follows:

$$P = Q(H_0 - H_1)/n_s$$

H_1 is the average suction total pressure and H_0 is the free stream total pressure. Also, the suction flow coefficient is defined.

$$C_Q = A/U_0 bc$$

The pressure loss coefficient is defined as follows:

$$C_P = (H_0 - H_1)/q_0$$

where the free stream dynamic pressure is q_0 . Substituting into the expression for P , the following equation results:

$$P = C_Q U_0 bc C_P q_0 / n_s.$$

The equivalent drag associated with the aircraft propulsion system can be written in the following form.

$$D = P n_p / U_0$$

Section suction drag and total drag coefficients, $C_{ds} \times 10^3$ and $C_{dt} \times 10^3$

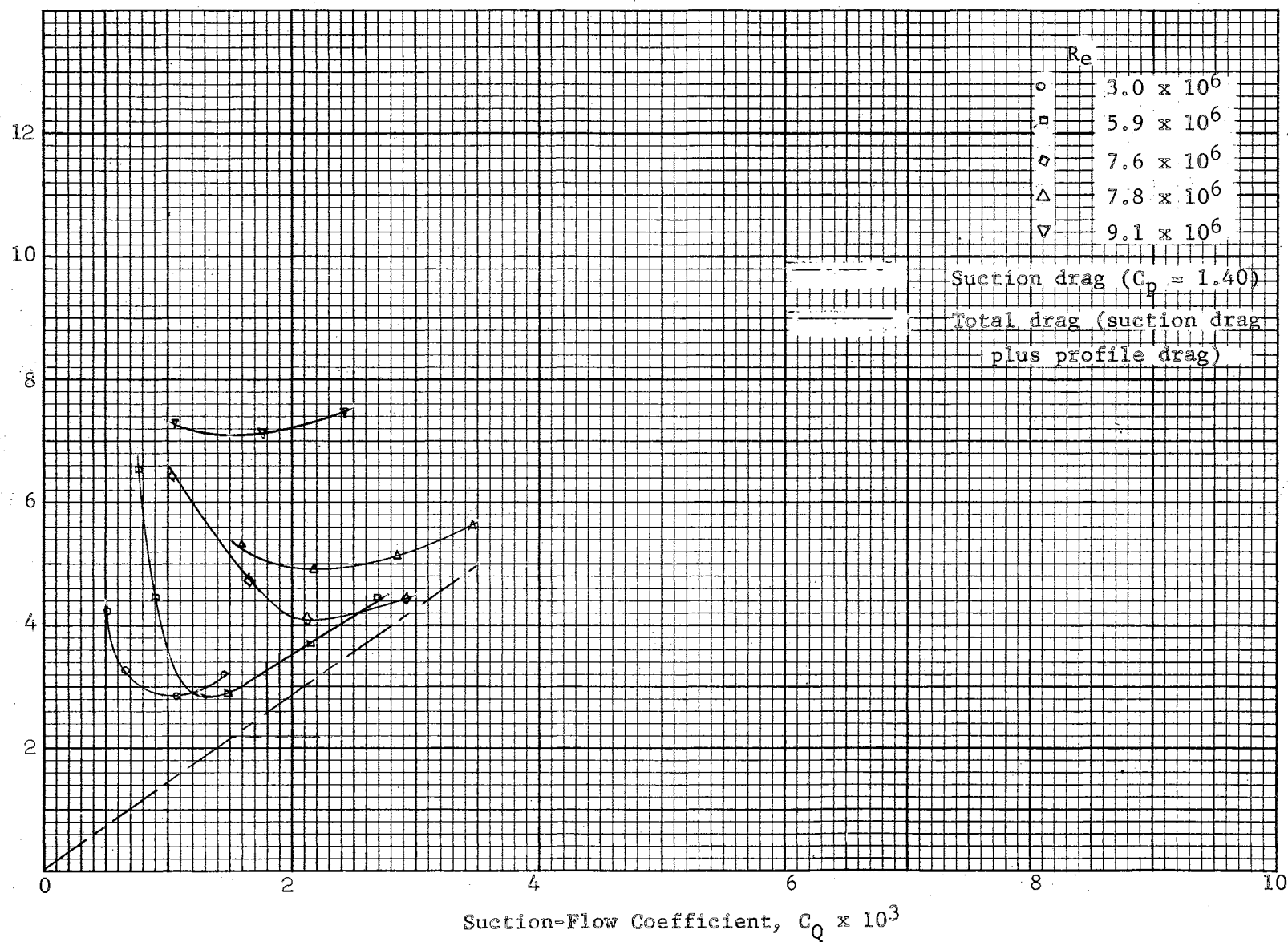


Figure 2. Variation of Section Drag Coefficients With Suction for a Porous Bronze NACA 64A010 Airfoil Model. $C_v/ct = 7.2 \times 10^{-9}$; $\alpha_0 = 0^\circ$; Configuration 2.

Section suction-drag and total drag coefficients, $C_{ds} \times 10^3$ and $C_{dt} \times 10^3$

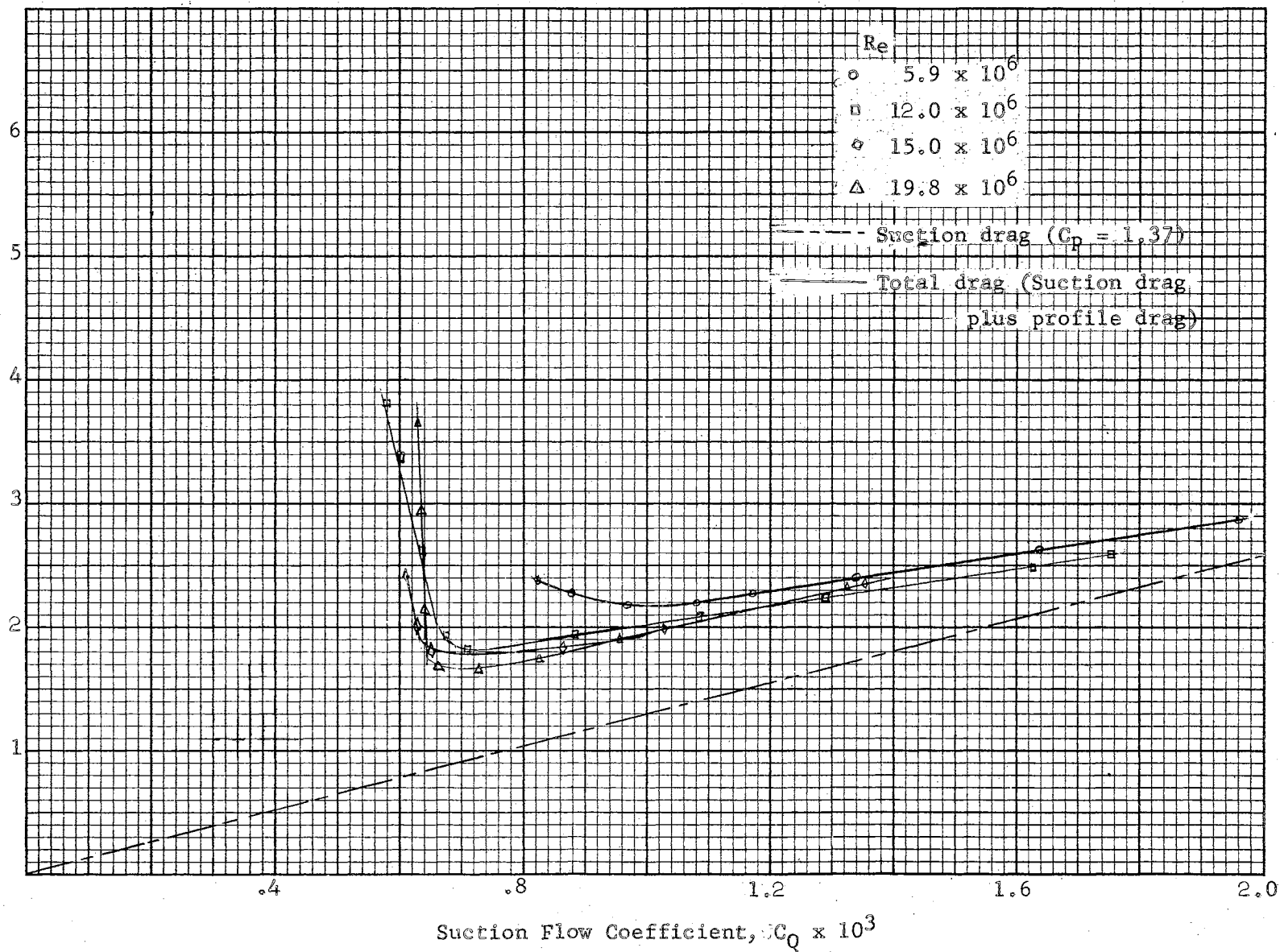


Figure 3. Variation of Section Drag Coefficient With Suction for a Porous Bronze NACA 64A010 Airfoil Model. $C_v/ct = 2.33 \times 10^{-10}$; $\alpha_0 = 0^\circ$; Configuration 3.

The efficiency of the propulsion system is η_p and the above equation may be written as follows:

$$C_{ds} b c q_o = P \eta_p / U_o$$

Again substituting for P in this expression, we obtain the following equation.

$$C_{ds} = C_Q C_p \eta_p / \eta_s$$

If the blower system operates as efficiently as the propulsion system, then the equation for the suction drag coefficient may be written in the following final form. (Braslow, page 451).

$$C_{ds} = C_Q C_p$$

Therefore the suction drag coefficient is shown to be directly dependent upon the suction flow coefficient assuming that the suction pressure coefficient measured inside the wing is a constant.

Comparison With Theoretical Results

The results of these experiments had to be compared to theoretical calculations on a qualitative basis since the chordwise suction flow was not completely uniform. However, the theoretical suction quantities compared extremely well with the results obtained experimentally from the third configuration for the optimum values of C_Q . The experimental values have been plotted with the theoretical values in Figure 4. (Braslow, page 441). The values for the first and second models were considerably greater due to the flow reversal near the leading and trailing edges. As a matter of interest, the suction requirements to produce full chord laminar stability for a flat plate were included.

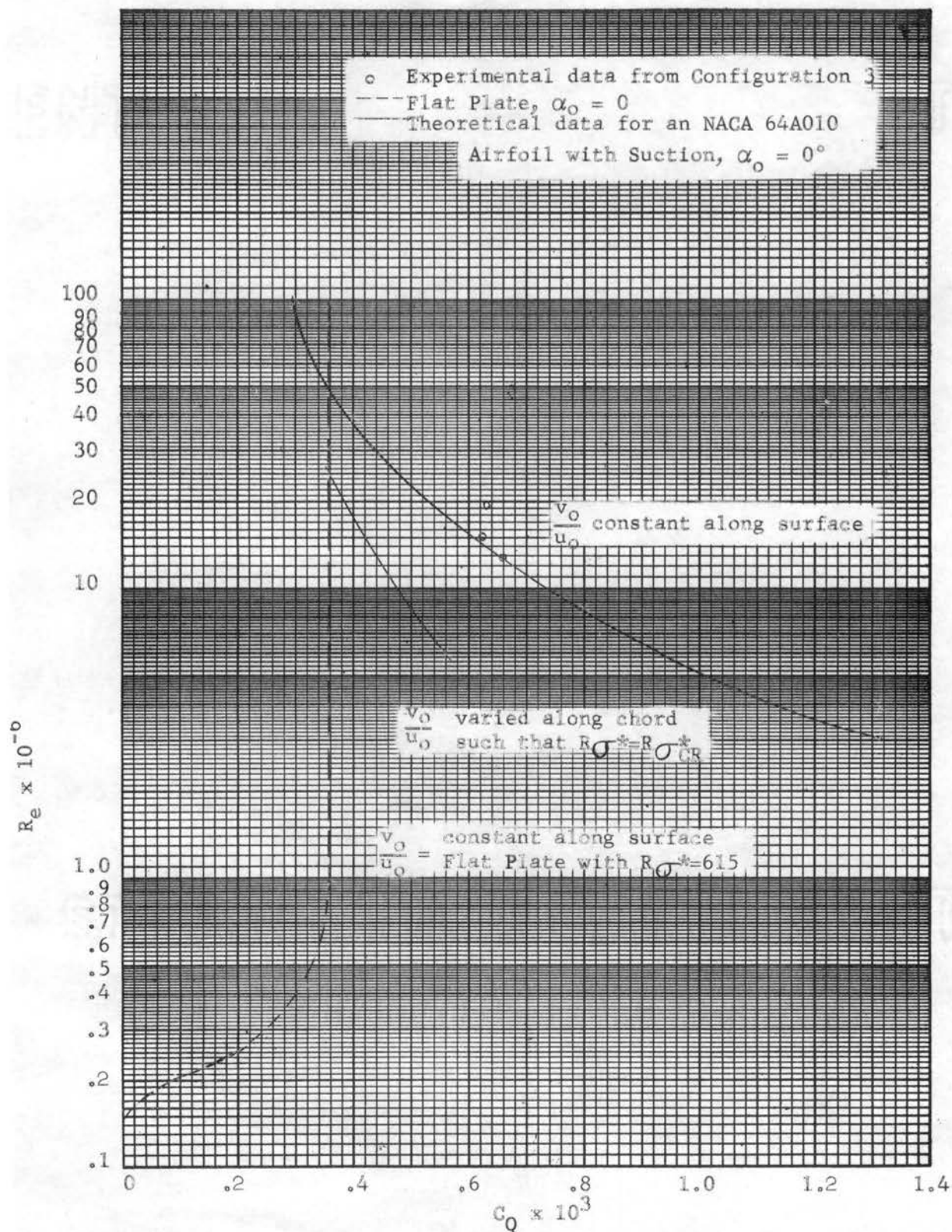


Figure 4. Theoretical Variation of Free Stream Re With Minimum Suction-Flow Coefficient Required to Produce Full-Chord Laminar Stability.

Profile Drag of an NACA 64A010 Airfoil Without Suction

The minimum section drag coefficients for this particular airfoil for smooth and rough conditions have been calculated by Loftin on page 18. Under ideal wind tunnel conditions, the value for a smooth airfoil at a zero degree angle of attack was found to be .0045. The rough airfoil gave a value of .0092. Braslow found that the porous airfoils utilized in the tests gave a value of C_{d_0} equal to .0052 on page 444.

Since the first and second configurations produced results similar to those of a rough airfoil, the maximum value of C_{d_0} equal to .0092 and an average value of C_{d_0} equal to .00685 were selected. The third configuration gave results similar to those obtained for a smooth airfoil. Therefore, values equal to .0052 and .0045 for C_{d_0} were selected. These values of the profile drag without suction and the results obtained from the three configurations were used to perform the necessary calculations to determine whether suction could be optimized based on power considerations.

CHAPTER IV

RESULTS

Calculations were performed using the data presented in Chapter III. The results have been tabulated in Table I for configuration one, in Table II for configuration two, and in Table III for the third configuration. The computations were made to the limit of the experimental data available without extrapolation. The profile drag with suction was tabulated as n .

$$n = C_{dT} - C_{dS}$$

The total reduction in profile drag compared to the values selected for the profile drag without suction were tabulated as k .

$$k = C_{dO} - n$$

The ratio of the profile drag reduction to the suction drag coefficient was tabulated as β .

$$\beta = k/C_{dS}$$

Included in the last line of calculations for each Reynolds number was one set of values for a value of suction flow coefficient greater than optimum based on drag considerations for comparison purposes and for use in plotting the results in Figures 5, 6, 7, 8 and 9. These figures show the variation between C_Q and β for each of the models tested. All Reynolds numbers except 9×10^6 , 12×10^6 , and 17.7×10^6 for configuration one were plotted. There were not sufficient values obtained to warrant the plotting of these values of Reynolds numbers.

TABLE I

RESULTS FOR CONFIGURATION ONE

| R_e $\times 10^6$ | C_{dT} $\times 10^3$ | C_{ds} $\times 10^3$ | n $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β | C_Q $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β |
|------------------------|---------------------------|---------------------------|----------------------|---------------------------|----------------------|---------|------------------------|---------------------------|----------------------|---------|
| 3.00 | 6.50 | 2.80 | 3.70 | 9.20 | 5.50 | 1.963 | 2.10 | 6.85 | 3.15 | 1.125 |
| | 6.00 | 2.85 | 3.15 | | 6.05 | 2.120 | 2.17 | | 3.70 | 1.299 |
| | 5.50 | 2.87 | 2.63 | | 6.57 | 2.285 | 2.20 | | 4.22 | 1.465 |
| | 4.90 | 2.90 | 2.00 | | 7.20 | 2.481 | 2.25 | | 4.85 | 1.672 |
| | 4.50 | 3.00 | 1.50 | | 7.70 | 2.565 | 2.30 | | 5.35 | 1.783 |
| | 4.30 | 3.05 | 1.25 | | 7.95 | 2.650 | 2.38* | | 5.60 | 1.832 |
| | 5.80 | 5.00 | 0.80 | | 8.40 | 1.680 | 3.80 | | 6.05 | 1.210 |
| 5.90 | 8.00 | 5.60 | 2.40 | 9.20 | 6.80 | 1.214 | 4.30 | 6.85 | 4.45 | 0.795 |
| | 7.85 | 5.70 | 2.15 | | 7.05 | 1.236 | 4.38 | | 4.70 | 0.824 |
| | 7.40 | 5.90 | 1.50 | | 7.70 | 1.304 | 4.50 | | 5.35 | 0.906 |
| | 7.20 | 6.05 | 1.15 | | 8.05 | 1.331 | 4.62 | | 5.70 | 0.944 |
| | 7.10 | 6.30 | 0.80 | | 8.40 | 1.331 | 4.75 | | 6.05 | 0.960 |
| | 7.08 | 6.40 | 0.68 | | 8.52 | 1.332 | 4.80 | | 6.17 | 0.963 |
| | 7.07 | 6.50 | 0.57 | | 8.63 | 1.327 | 4.90* | | 6.28 | 0.969 |
| | 8.50 | 8.00 | 0.50 | | 8.70 | 1.089 | 6.10 | | 6.35 | 0.794 |
| 9.00 | 8.90 | 6.05 | 2.85 | 9.20 | 6.35 | 1.051 | 4.63* | 6.85 | 4.00 | 0.662 |
| | 10.0 | 8.35 | 1.65 | | 7.55 | 0.904 | 6.30 | | 5.20 | 0.623 |
| 12.00 | 9.80 | 6.80 | 3.00 | 9.20 | 6.20 | 0.912 | 5.20* | 6.85 | 3.85 | 0.567 |
| | 11.0 | 8.50 | 3.50 | | 5.70 | 0.671 | 6.40 | | 3.30 | 0.388 |
| 16.7 | 10.2 | 6.40 | 3.80 | 9.20 | 5.40 | 0.844 | 4.80* | 6.85 | 3.05 | 0.477 |
| | 11.0 | 8.90 | 2.10 | | 7.10 | 0.798 | 6.70 | | 4.75 | 0.533 |

* Optimum value of C_Q based drag reduction.

TABLE II

RESULTS FOR CONFIGURATION TWO

| Re $\times 10^6$ | C_{dT} $\times 10^3$ | C_{ds} $\times 10^3$ | n $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β | C_Q $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β |
|-----------------------|---------------------------|---------------------------|----------------------|---------------------------|----------------------|---------|------------------------|---------------------------|----------------------|---------|
| 3.00 | 4.30 | 0.65 | 3.65 | 9.20 | 5.55 | 8.530 | 0.50 | 6.85 | 3.20 | 4.920 |
| | 3.50 | 0.85 | 2.65 | | 6.55 | 7.700 | 0.63 | | 4.20 | 4.940 |
| | 3.20 | 1.05 | 2.15 | | 7.05 | 6.710 | 0.75 | | 4.70 | 4.470 |
| | 3.00 | 1.20 | 1.80 | | 7.40 | 6.160 | 0.88 | | 5.05 | 4.210 |
| | 2.90 | 1.40 | 1.50 | | 7.70 | 5.500 | 1.00 | | 5.35 | 3.820 |
| | 2.85 | 1.50 | 1.35 | | 7.85 | 5.230 | 1.12* | | 5.50 | 3.660 |
| | 3.20 | 2.10 | 1.10 | | 8.10 | 3.850 | 1.50 | | 5.75 | 2.740 |
| 5.90 | 6.70 | 1.00 | 5.70 | 9.20 | 3.50 | 3.50 | 0.75 | 6.85 | 1.15 | 1.150 |
| | 6.00 | 1.10 | 4.90 | | 4.30 | 3.910 | 0.79 | | 1.95 | 1.771 |
| | 5.50 | 1.15 | 4.35 | | 4.85 | 4.220 | 0.80 | | 2.50 | 2.175 |
| | 5.00 | 1.21 | 3.79 | | 5.41 | 4.460 | 0.86 | | 3.06 | 2.530 |
| | 4.70 | 1.30 | 3.40 | | 5.80 | 4.460 | 0.88 | | 3.45 | 2.650 |
| | 3.50 | 1.40 | 2.10 | | 7.10 | 5.070 | 1.00 | | 4.75 | 3.390 |
| | 3.00 | 1.58 | 1.42 | | 7.78 | 4.930 | 1.13 | | 5.43 | 3.430 |
| | 2.80 | 1.75 | 1.05 | | 8.15 | 4.650 | 1.25 | | 5.80 | 3.310 |
| | 2.76 | 1.99 | 0.77 | | 8.43 | 4.240 | 1.40* | | 6.08 | 3.060 |
| | 4.25 | 3.85 | 0.40 | | 8.80 | 2.285 | 2.75 | | 6.45 | 1.670 |
| 7.60 | 6.60 | 1.40 | 5.20 | 9.20 | 4.00 | 2.859 | 1.00 | 6.85 | 1.65 | 1.18 |
| | 6.30 | 1.60 | 4.70 | | 4.50 | 2.819 | 1.12 | | 2.15 | 1.34 |
| | 5.97 | 1.75 | 4.12 | | 5.08 | 2.900 | 1.25 | | 2.73 | 1.56 |
| | 5.50 | 1.99 | 3.51 | | 5.69 | 2.860 | 1.37 | | 3.34 | 1.68 |
| | 5.10 | 2.10 | 3.00 | | 6.20 | 2.950 | 1.50 | | 3.85 | 1.83 |
| | 4.80 | 2.30 | 2.50 | | 6.70 | 2.920 | 1.63 | | 4.35 | 1.89 |
| | 4.45 | 2.49 | 1.96 | | 7.24 | 2.905 | 1.75 | | 4.89 | 1.96 |

TABLE II (Continued)

| Re $\times 10^6$ | C_{dT} $\times 10^3$ | C_{ds} $\times 10^3$ | n $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β | C_Q $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β |
|-----------------------|---------------------------|---------------------------|----------------------|---------------------------|----------------------|---------|------------------------|---------------------------|----------------------|---------|
| | 4.25 | 2.60 | 1.65 | | 7.55 | 2.905 | 1.87 | | 5.20 | 2.00 |
| | 4.15 | 2.80 | 1.25 | | 7.95 | 2.840 | 2.00 | | 5.60 | 2.00 |
| | 4.05 | 3.00 | 1.05 | | 8.15 | 2.720 | 2.12 | | 5.80 | 1.93 |
| | 4.05 | 3.20 | 0.85 | | 8.35 | 2.610 | 2.25* | | 6.00 | 1.88 |
| | 4.50 | 4.25 | 0.25 | | 8.15 | 1.920 | 3.00 | | 6.40 | 1.51 |
| 7.80 | 5.35 | 2.10 | 3.25 | 9.20 | 5.95 | 2.830 | 1.50 | 6.85 | 3.60 | 1.710 |
| | 5.25 | 2.30 | 2.95 | | 6.25 | 2.720 | 1.62 | | 3.90 | 1.690 |
| | 5.05 | 2.49 | 2.56 | | 6.64 | 2.670 | 1.75 | | 4.29 | 1.730 |
| | 5.00 | 2.60 | 2.40 | | 6.80 | 2.610 | 1.87 | | 4.45 | 1.710 |
| | 4.95 | 2.80 | 2.15 | | 7.05 | 2.519 | 2.00 | | 4.70 | 1.680 |
| | 4.92 | 3.00 | 1.92 | | 7.28 | 2.424 | 2.12 | | 4.83 | 1.610 |
| | 4.94 | 3.20 | 1.74 | | 7.46 | 2.330 | 2.25* | | 5.11 | 1.600 |
| | 5.70 | 4.90 | 0.80 | | 8.40 | 1.712 | 3.50 | | 6.05 | 1.240 |
| 9.10 | 7.30 | 1.40 | 5.90 | 9.20 | 3.30 | 2.359 | 1.00 | 6.85 | 0.95 | 0.679 |
| | 7.25 | 1.55 | 5.70 | | 3.50 | 2.260 | 1.12 | | 1.15 | 0.720 |
| | 7.20 | 1.75 | 5.45 | | 3.75 | 2.150 | 1.25 | | 1.40 | 0.800 |
| | 7.19 | 1.99 | 5.20 | | 4.00 | 2.010 | 1.37 | | 1.65 | 0.833 |
| | 7.18 | 2.10 | 5.08 | | 4.12 | 1.965 | 1.50* | | 1.77 | 0.842 |
| | 7.60 | 3.50 | 4.10 | | 5.10 | 1.455 | 2.50 | | 2.75 | 0.788 |

* Optimum value of C_Q based on drag reduction.

TABLE III

RESULTS FOR CONFIGURATION THREE

| R_e $\times 10^6$ | C_{dT} $\times 10^3$ | C_{ds} $\times 10^3$ | n $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β | C_Q $\times 10^3$ | C_{do} $\times 10^3$ | k $\times 10^3$ | β |
|------------------------|---------------------------|---------------------------|----------------------|---------------------------|----------------------|---------|------------------------|---------------------------|----------------------|---------|
| 5.90 | 2.35 | 1.10 | 1.35 | 5.20 | 3.85 | 3.500 | 0.820 | 4.50 | 3.15 | 2.865 |
| | 2.30 | 1.20 | 1.10 | | 4.10 | 3.419 | 0.850 | | 3.40 | 2.839 |
| | 2.20 | 1.24 | 0.96 | | 4.24 | 3.420 | 0.900 | | 3.54 | 2.850 |
| | 2.18 | 1.26 | 0.92 | | 4.28 | 3.400 | 0.950 | | 3.58 | 2.842 |
| | 2.15 | 1.35 | 0.80 | | 4.40 | 3.260 | 1.000 | | 3.70 | 2.740 |
| | 2.19 | 1.40 | 0.79 | | 4.41 | 3.150 | 1.050* | | 3.71 | 2.645 |
| | 2.97 | 2.60 | 0.37 | | 4.83 | 1.857 | 1.980 | | 4.13 | 1.590 |
| 12.0 | 3.90 | 0.70 | 3.20 | 5.20 | 2.00 | 2.860 | 0.570 | 4.50 | 1.30 | 1.859 |
| | 3.50 | 0.74 | 2.76 | | 2.44 | 3.295 | 0.590 | | 1.74 | 2.355 |
| | 3.30 | 0.75 | 2.55 | | 2.65 | 3.535 | 0.600 | | 1.95 | 2.595 |
| | 3.00 | 0.78 | 2.22 | | 2.98 | 3.821 | 0.620 | | 2.28 | 2.925 |
| | 2.50 | 0.79 | 1.71 | | 3.49 | 4.420 | 0.630 | | 2.79 | 3.530 |
| | 2.30 | 0.80 | 1.50 | | 3.70 | 4.620 | 0.650 | | 3.00 | 3.750 |
| | 2.00 | 0.85 | 1.15 | | 4.05 | 4.760 | 0.670 | | 3.35 | 3.940 |
| | 1.75 | 0.91 | 0.74 | | 4.46 | 4.910 | 0.690* | | 3.76 | 4.140 |
| | 2.70 | 2.30 | 0.40 | | 4.80 | 2.089 | 1.770 | | 4.10 | 1.780 |
| 15.0 | 2.40 | 0.80 | 1.60 | 5.20 | 3.60 | 4.500 | 0.615 | 4.50 | 2.90 | 3.625 |
| | 2.00 | 0.82 | 1.18 | | 4.02 | 4.920 | 0.620 | | 3.32 | 3.925 |
| | 1.75 | 0.83 | 0.92 | | 4.28 | 5.160 | 0.650 | | 3.58 | 4.310 |
| | 1.75 | 0.90 | 0.85 | | 4.35 | 4.840 | 0.700 | | 3.65 | 4.060 |
| | 1.75 | 1.00 | 0.75 | | 4.45 | 4.450 | 0.750* | | 3.75 | 3.750 |
| | 2.70 | 2.30 | 0.40 | | 4.80 | 2.085 | 1.770 | | 4.10 | 1.782 |
| 19.8 | 3.80 | 0.80 | 3.00 | 5.20 | 2.20 | 2.750 | 0.623 | 4.50 | 1.50 | 1.876 |
| | 3.50 | 0.81 | 2.69 | | 2.51 | 3.100 | 0.630 | | 1.81 | 2.234 |
| | 3.00 | 0.82 | 2.18 | | 3.02 | 3.680 | 0.640 | | 2.32 | 2.830 |
| | 2.50 | 0.82 | 1.68 | | 3.52 | 4.285 | 0.640 | | 2.82 | 3.439 |
| | 2.00 | 0.83 | 1.17 | | 4.03 | 4.860 | 0.650 | | 3.33 | 4.010 |
| | 1.75 | 0.83 | 0.92 | | 4.28 | 5.155 | 0.650 | | 3.58 | 4.320 |
| | 1.70 | 0.85 | 0.85 | | 4.35 | 5.120 | 0.680* | | 3.65 | 4.290 |
| | 2.35 | 1.79 | 0.56 | | 4.64 | 2.590 | 1.390 | | 3.94 | 2.200 |

* Optimum value of C_Q based on drag reduction.

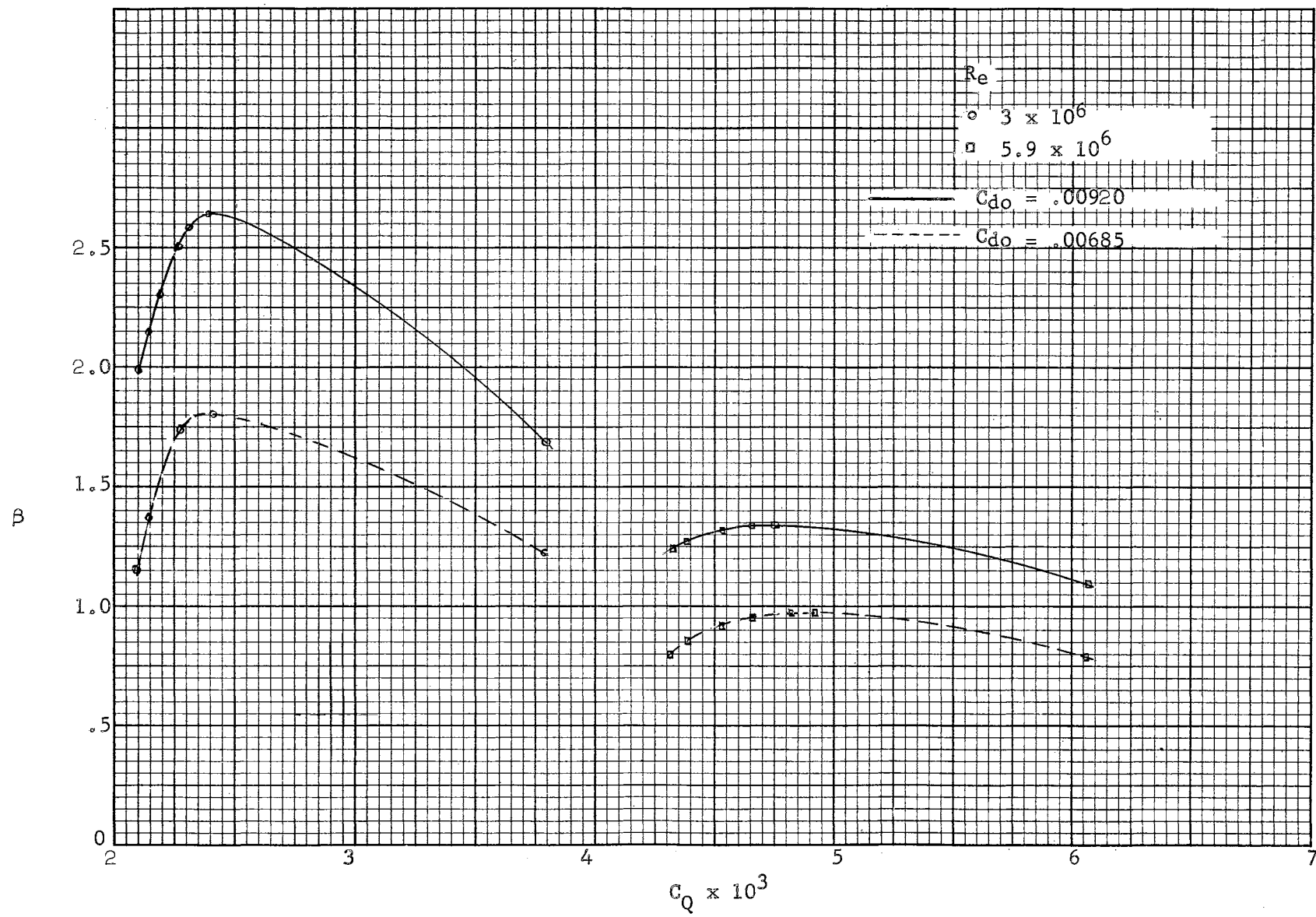


Figure 5. Variation of (β) With Suction-Flow Coefficient. Configuration 1.

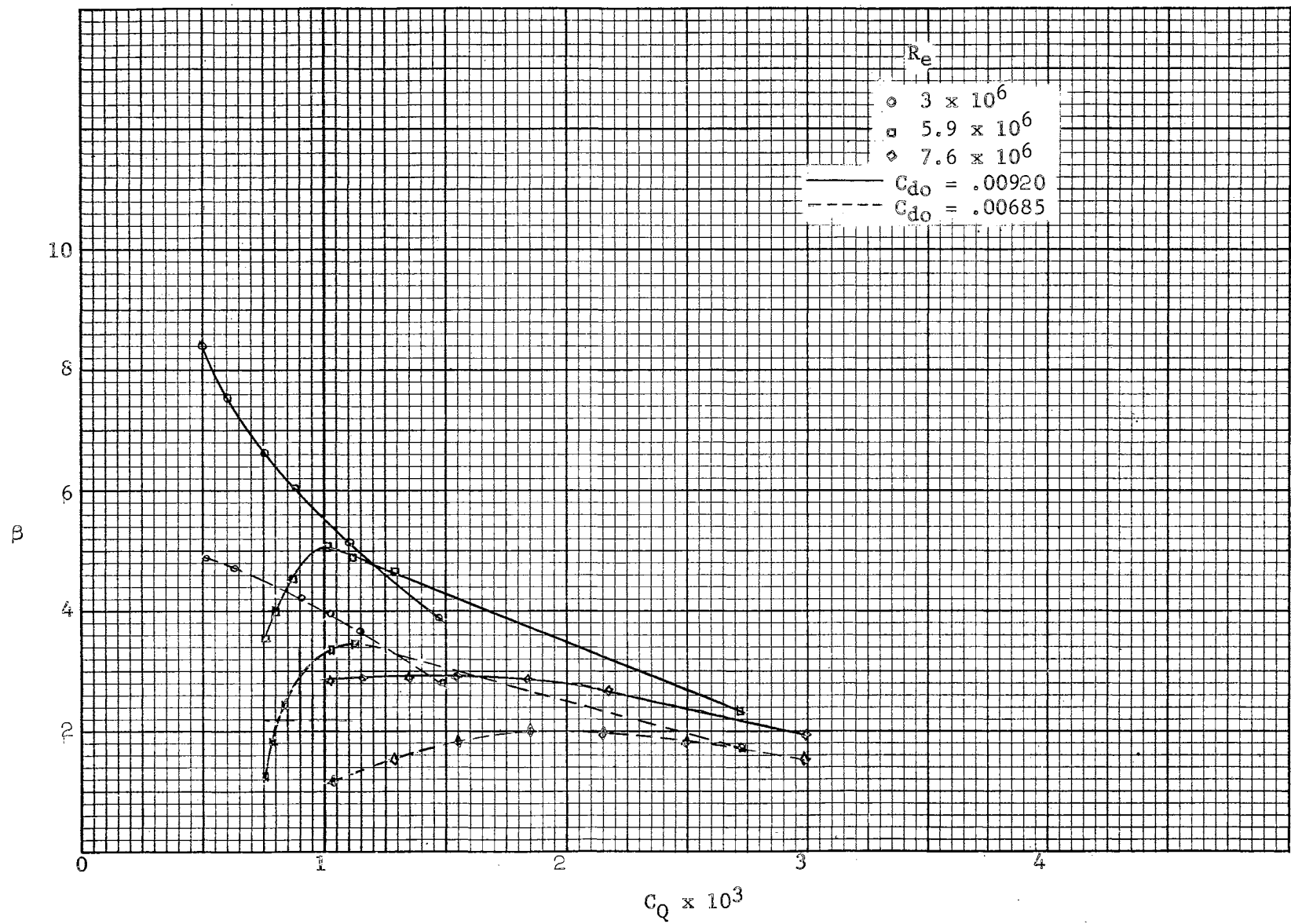


Figure 6. Variation of (β) With Suction-Flow Coefficient. Configuration 2.

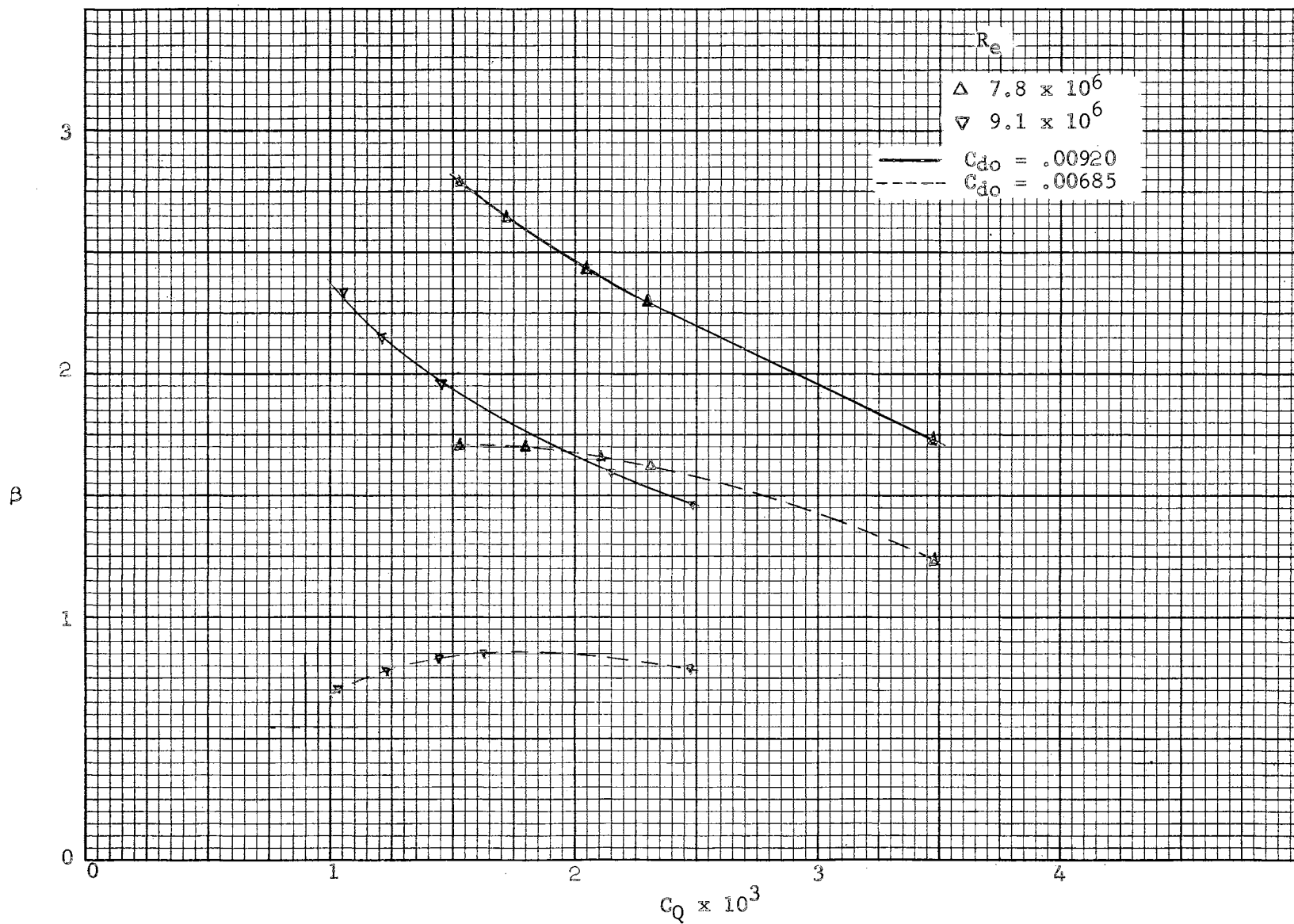


Figure 7. Variation of (β) With Suction-Flow Coefficient. Configuration 2.

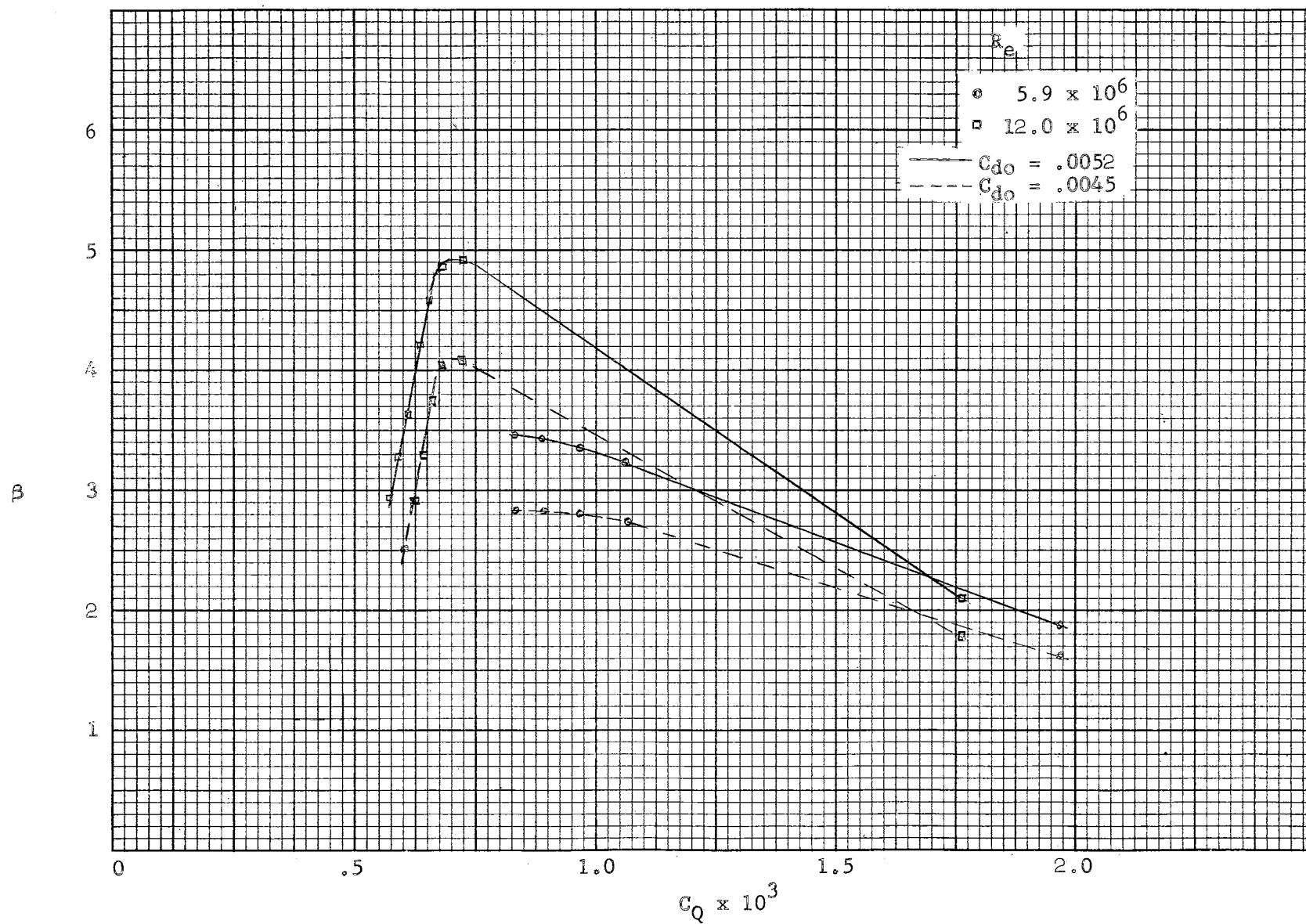


Figure 8. Variation of (β) With Suction-Flow Coefficient. Configuration 3.

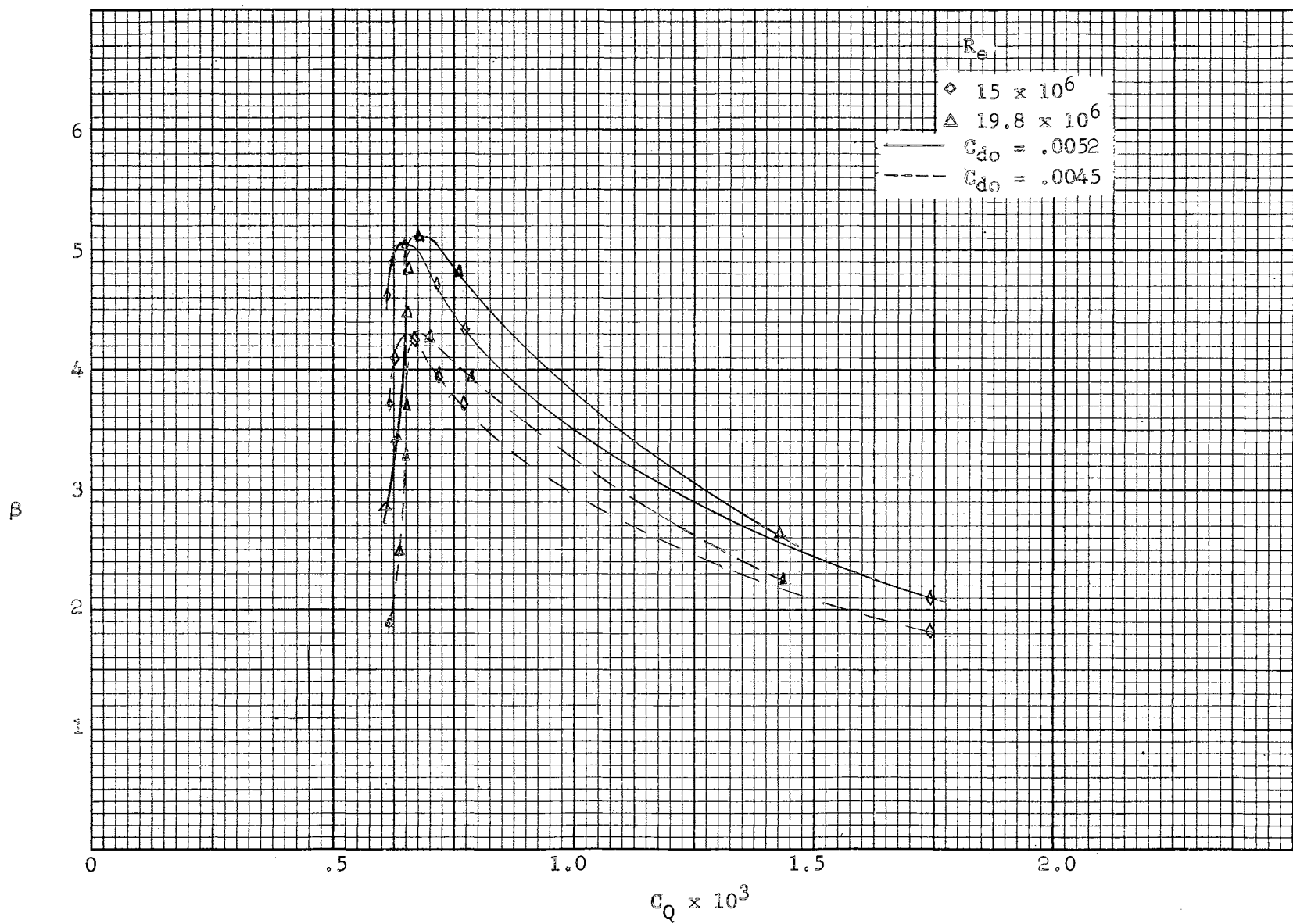


Figure 9. Variation of (β) With Suction-Flow Coefficient. Configuration 3.

CHAPTER V

INTERPRETATION OF RESULTS

The purpose was to determine the optimum amount of suction that could be applied and still obtain a favorable ratio of profile drag reduction to the power required; that is, the selection of a value of β equal to or greater than unity for some value of C_Q based on power requirements so that the power required would be a minimum. Some rather interesting results were obtained from the previous calculations. The values of β , tabulated in Tables I, II, and III for the different configurations varied considerably. It was noted that when β was equal to unity, the power input just balanced the reduction in drag obtained by area suction. Also, the more that β increased above unity the greater was the reduction of profile drag for the power supplied. As the value of β decreased below unity, the incremental value of drag reduction decreased accordingly for the power supplied.

The results that were expected were that as the values of C_Q were decreased that the values of β would decrease also. The rather surprising results that were obtained from the previous calculations showed that the values of β actually increased or remained at a fairly constant value for over 54% of the cases examined as the values of C_Q were decreased. This meant that the optimum suction flow coefficient on a basis of power consumption gave a greater reduction in profile drag for the power re-

quired or at least the same reduction in drag than the optimum suction flow coefficient based on drag reduction in these cases. In each of the cases the optimum value of C_Q based on power was less than the optimum value of C_Q based on drag. These cases were pointed out as each configuration was examined. Each model was examined on the basis of minimum power requirements and were evaluated as to their practicability at the various Reynolds numbers at which they were tested.

Configuration One

The first model was seen to perform as had been expected. As the values of suction were decreased, the corresponding values of β generally decreased for all Reynolds numbers at which it was tested. It was noted that the particular values obtained depended very strongly on the particular value of profile drag without suction. Only at a Reynolds number of 3×10^6 were there favorable values of β obtained for both values of selected profile drag coefficients without suction. In fact, it was clearly indicated that this configuration would only be suitable for very low Reynolds numbers or for moderate Reynolds numbers with an extremely rough airfoil surface.

Configuration Two

The second model showed considerable improvement compared to the first configuration. The values of β increased for all values of Reynolds numbers as the suction flow coefficient was decreased. Only at a Reynolds number of 5.9×10^6 was there a notable decrease in β after an initial in-

crease in this value as C_Q was decreased. The optimum value of C_Q based on power for this Reynolds number was about .0010. This was about a 70% decrease for the optimum value of C_Q based on maximum drag requirements in suction flow coefficient. At all other Reynolds numbers and at both C_{d_0} values selected the percent reduction in C_Q was on the order of 60%. Thus, configuration two appeared to be worthy for consideration in actual aircraft design.

Configuration Three

The calculations for the third model showed the best improvement of all the models tested even though the values of C_{d_0} selected were less than either of the values for the first and second configurations. Hence, the percent reduction in C_Q was less than in the first two models, but was never less than unity for all Reynolds numbers tested. The reduction in C_Q was on the order of 20% for the optimum value of C_Q based on power as compared to the value of optimum C_Q based on drag reduction requirements. The optimum values for C_Q for minimum power were those values obtained at the limits of the calculations. A more complete set of data might have produced even lower values of C_Q than those obtained in these computations. It was suggested that this model might prove of value for use, not only at moderate Reynolds numbers, which would include the approach and landing speeds range, but also for use at cruise speeds for aircraft. Consequently, the most desirable configuration under consideration appeared to be the third.

CHAPTER VI

SUMMARY AND CONCLUSIONS

It was expected that when the suction flow coefficient was reduced from the optimum value of C_Q based on drag considerations for each of the three configurations of the NACA 64A010 airfoil that used boundary-layer-control with area suction, the result would be that the ratio of drag reduction to the power supplied would decrease accordingly. In the calculations it was expected that this ratio would be equal to unity at some point thus giving an optimum value of suction flow coefficient based on power requirements such that the reduction in drag just balanced the power required for suction. This assumption was commensurate with the results obtained from the first configuration. However, the results obtained from the second and third configurations in the majority of cases were in direct contrast to the expected results. The rather surprising result that the ratio β actually increased with a reduction in suction was observed. This meant that an increase in the performance of an aircraft could be obtained using area suction with a considerable savings in the suction equipment required. The saving in weight could then be converted into an increase in payload and range with decreased landing and takeoff speeds all of which would reduce the cost of aircraft operation.

The problems that were found to be of the utmost concern in the

utilization of area suction were those that dealt with the delay in transition which involved the structural aspects of a wing utilizing area suction. That is, the problem of delaying transition to a point further rearward along the chord by means of a differently shaped or finished surface that would produce optimum values of suction on a power basis and a drag basis better than those obtained in this paper warrant further investigation. Also as a further study, it is suggested that an optimization of range or endurance be accomplished on the basis of the savings in weight that have been indicated in this work.

Much work has been done in the past in the investigation of boundary-layer-control using area suction. The results both theoretical and experimental have proved that the principle is sound. It is left to the design engineer to put this principle to practice. It is hoped that the results in this paper that indicate that a reduction in weight can be obtained and the increase in performance maintained will be of benefit in making the use of area suction for boundary-layer-control useful in practical applications.

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APPENDIX

SYMBOLS

| | |
|------------|--|
| α_o | Section angle of attack, degrees. |
| b | Span of porous surface, ft. |
| β | k/C_{ds} . |
| c | Airfoil chord, ft. |
| C_p | Suction air pressure coefficient $(H_o - H_i)/q_o$. |
| C_Q | Suction flow coefficient (Q/bcU_o) . |
| C_{ds} | Section suction drag coefficient $(C_Q C_p)$. |
| C_{dT} | Section total drag coefficient. |
| C_{do} | Profile drag coefficient without suction. |
| c_v | Porosity factor, ft^2 . |
| D | Drag $(C_{ds}bcq_o)$, lb. |
| H_o | Free stream total pressure, lb/in^2 . |
| H_i | Total pressure in model interior, lb/in^2 . |
| k | $C_{do} - n$. |
| n | $C_{dT} - C_{ds}$. |
| n_s | Efficiency of suction system. |
| n_p | Efficiency of propulsion system. |
| P | Power, horsepower. |
| Q | Total quantity rate of flow through both airfoil surfaces, lb/ft^3 . |
| q_o | Free stream dynamic pressure, lb/ft^2 . |

R_e Free stream Reynolds number based on airfoil chord.

R_{σ}^* Reynolds number based on boundary layer displacement thickness.

$R_{\sigma CR}^*$ Boundary layer critical Reynolds number.

t Thickness of porous material, in.

U_o Free stream velocity, fps.

v_o Velocity through the airfoil surface, fps.

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