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EXPERIMENTAL INVESTIGATION OF BOUNDARY-LAYER SUCTION THROUGH SLOTS TO OBTAIN EXTENSIVE LAMINAR BOUNDARY LAYERS ON A 15-PERCENT-THICK AIRFOIL SECTION AT HIGH REYNOLDS NUMBERS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A two-dimensional wind-tunnel investigation has been made in an effort to determine the extent to which boundary-layer removal through slots is effective as a means for maintaining extensive laminar layers at high Reynolds numbers. The model investigated was a 6-series type of airfoil section having a thickness of 15-percent chord and had a suction-slot arrangement designed to maintain essentially full-chord laminar flow at a Reynolds number of 20.0×10^6. Seventeen suction slots were employed on the upper surface and thirteen slots were employed on the lower surface of the 5-foot-chord model. The investigation was made through a range of Reynolds number from 6.0×10^6 to 19.0×10^6.

Essentially full-chord laminar flow with accompanying total drag coefficients (wake drag coefficient plus drag coefficient equivalent of the suction power) of about 0.0012 were obtained for Reynolds numbers as high as 16.0×10^6 to 17.0×10^6. The greatest difficulty was experienced throughout the investigation, however, in maintaining the surfaces of the model in a sufficiently good condition to prevent forward movements of the transition point. Small particles of lint, noise, and minute flows of air into the boundary layer through machined joints in the surface caused large forward movements of the transition point. In many instances transition occurred at forward positions even though no perceptible disturbance was found, but further rubbing and polishing of the surface restored the extent of laminar flow. The degree of surface excellence required in attempting to obtain extensive laminar layers on aircraft through the use of multiple slots would seem to be at least as high as that found necessary in the past in attempting to obtain extensive laminar layers on airplane wings employing low-drag type of airfoil sections without boundary-layer control.

INTRODUCTION

The use of boundary-layer removal through slots as a means for maintaining extensive regions of laminar flow on the surfaces of airfoil sections has been the subject of a number of experimental investigations. Perhaps the best known of these investigations are those made by Pfenninger (ref. 1) and Holstein (refs. 2 and 3), in which essentially full-chord laminar flow with net drag savings was obtained at Reynolds numbers of the order of 3.0×10^6 to 4.0×10^6.

The investigations of references 1 to 3, although of some interest, leave unanswered the very important question as to the effectiveness of boundary-layer suction through slots as a means of obtaining extensive laminar layers at high Reynolds numbers of the order of 25.0×10^6. The investigation reported by Burrows and Schwartzberg (ref. 4) was designed to answer this question. The investigation of reference 4 consisted in two-dimensional wind-tunnel tests of an NACA 64A010 airfoil section model which had a distribution of suction slots designed to maintain essentially full-chord laminar flow with net drag savings at a Reynolds number of 25.0×10^6. The highest Reynolds number for which full-chord laminar flow was obtained on this model was of the order of 10.0×10^6. Full-chord laminar flow was not obtained at Reynolds numbers higher than 10.0×10^6 because of disturbances associated with very minute imperfections in the surfaces of the model and in the contours of the slots. The results of this investigation were not interpreted as meaning that full-chord laminar flow could not be obtained at Reynolds numbers higher than 10×10^6 by the use of suction slots, but rather, that the practical difficulties associated with constructing and maintaining wing surfaces and slot contours in a sufficiently smooth and fair condition were so great as to the make the application of this method of laminar boundary-layer control to full-scale aircraft seem rather unpromising.

Dr. W. Pfenninger felt that extensive regions of laminar flow could be obtained at higher Reynolds numbers by employing a different suction-slot arrangement on a different airfoil and suggested that an investigation be made of a model of his design. In the hope that boundary-layer suction through slots could prove to be a more promising means of obtaining extensive laminar layers at high Reynolds numbers than was indicated by the results of reference 4, it was decided to make an experimental investigation in the Langley low-turbulence pressure tunnel of a model designed by Dr. Pfenninger and built by the Northrop Company under the sponsorship of the U. S. Air Force. The results of this investigation are contained in the present paper.

The model employed in the investigation was of a slightly modified NACA 66_2-(1.8)15 airfoil section, was of 5-foot chord, and was designed to maintain essentially full-chord laminar flow at a Reynolds number of 20.0×10^6. Seventeen slots were employed on the upper surface of the slightly cambered airfoil model and thirteen slots were employed on the lower surface. The investigation consisted in stethoscopic surveys of the boundary layer on the model, measurements of the wake drag, and flow and pressure loss in each slot for a range of angle of attack, flow rate, and Reynolds number. A few measurements were also made of the surface pressure distribution and lift.

SYMBOLS

c	airfoil chord
x	distance measured along airfoil chord
y	distance measured normal to airfoil chord
l	spanwise length of suction slot
θ	boundary-layer momentum thickness
U_o	free-stream velocity
U	local velocity just outside boundary layer
u	local velocity inside boundary layer
q_o	free-stream dynamic pressure
p_o	free-stream static pressure
p	local static pressure on surface of airfoil
H_o	free-stream total pressure
H_i	total pressure in suction chamber
S	pressure coefficient, $\frac{H_o - p}{q_o}$
α	section angle of attack

c_l	section lift coefficient
c_{d_o}	section drag coefficient measured in wake
ΔQ	flow removed through an individual slot
Δc_Q	incremental flow coefficient, $\frac{\Delta Q}{l c U_o}$
C_Q	total flow coefficient, sum of incremental flow coefficients
C_p	total pressure loss coefficient, $\frac{H_o - H_i}{q_o}$
c_{d_B}	blower drag coefficient, $C_p C_Q$
c_{d_T}	total drag coefficient, $c_{d_o} + c_{d_B}$
ν	kinematic viscosity
R	airfoil-chord Reynolds number, $\frac{U_o c}{\nu}$
R_θ	boundary-layer Reynolds number, $\frac{U\theta}{\nu}$

APPARATUS AND TESTS

Model and Suction Flow Apparatus

The basic thickness form of the airfoil section chosen for the present investigation was a slightly modified NACA 66_2-015. The theoretical pressure distribution at zero lift for the NACA 66_2-015 section and for the modified basic thickness form are shown in figure 1(a). The airfoil was cambered with an $a = 0.6$ mean line having a design lift coefficient of 0.18. The theoretical pressure distribution about the cambered airfoil is shown in figure 1(b) for lift coefficients of 0.1 and 0.2. The ordinates of the five-foot-chord airfoil section employed in the investigation are given in table I.

The construction of the model is illustrated schematically by the cut-away drawing presented in figure 2(a) and by the photographs of figures 2(b) and 2(c). The model was composed of two duralumin castings bolted together at the 32.5-percent-chord station. The front casting had an unslotted surface about 0.25 inch thick and was hollow except for reinforcing ribs. The contact surfaces or faces of the front and rear parts of the model were very carefully machined so that a tight fit was obtained. The rear casting was compartmented so as to provide chambers or passages for the suction flow. The portion of the surface of the rear part of the model which contained the slots was formed from 0.25- to 0.50-inch-thick duralumin slabs screwed onto the cast core. The method of forming and adjusting the slots themselves is illustrated by the small drawing in the upper right-hand corner of figure 2(a). The entire surface of the model was carefully machined so that a very smooth finish was obtained.

The center line of the suction slots made an angle of 50° to 55° with the surface normal and the passages of the slots were diverged at an included angle of 4° to form a diffuser. The front lip was rounded in contrast to the rear lip, which was left sharp. As can be seen from figure 2(a), the suction slot chambers were divided into three spanwise sections from which the flow removal could be independently controlled. The attempt to obtain extensive laminar layers was confined to that portion of the surface which covered the center row of suction chambers. The only purpose of the outer suction chambers was to reduce the possibility of turbulence moving inboard onto that portion of the surface of interest as a result of disturbances which might originate at the spanwise ends of this surface if no suction were employed outboard. The lines formed by the locus of points through the spanwise ends of the slots converged at an angle somewhat greater than that corresponding to the spread of turbulence behind a point disturbance (half angle of 7.5°). The spanwise widths of the slots covering the center row of suction chambers are given in table II together with the slot widths and spacing.

The quantity flow removed from each slot was measured by a calibrated venturi meter which was screwed into one side of each suction chamber. The size of the meter employed for each chamber is given in table II. For the rates of flow involved, the velocity in the chambers was sufficiently low so that the total pressure of the suction air was measured by flush orifices located in the bottom surface of the chambers. Most of the chambers were provided with small turning vanes which served the double purpose of guiding the air and supporting the surface. The surface pressure orifices shown in the sketch (fig. 2(a)) were formed by drilling a small hole through a length of threaded brass stock which was then screwed into a tapped hole in the surface. The chordwise locations of the pressure orifices are given in table III.

The method for controlling the flow in the individual slots is shown by the sketch presented in figure 3. Tubes led from each venturi meter to needle valves located on one side of the suction control box. (Only one tube and one needle valve is shown in the sketch.) The other side of the box was connected to the inlet of a variable-speed blower. A number of baffles were located between the blower inlet and the needle valves. These baffles extended completely across the box and were made of perforated steel. The box was lined with acoustical tile. The primary purpose of the baffles and acoustical tile was to reduce the intensity of the blower noise reaching the surface of the model and to damp any oscillations in the blower inlet pressure. Further, the pressure drop through the baffles was large as compared with that through the model and associated tubing so that the flow in one or more individual slots could be varied through a rather wide range without materially altering the flow in other slots.

Wind Tunnel and Test Methods

All of the tests of the present investigation were made in the Langley low-turbulence pressure tunnel (ref. 5). The test section of this tunnel is 3 feet by $7\frac{1}{2}$ feet and the model, when mounted, completely spanned the 3-foot dimension. Variations in Reynolds number are obtained by varying the tunnel speed and by compressing the air in the tunnel. In the present investigation, the tunnel pressure was regulated so that the tunnel free-stream Mach number did not exceed about 0.4 for any of the Reynolds numbers for which tests were made. Local Mach numbers of as much as 0.573, however, were reached on the surfaces of the model in some cases. Drag measurements were made in the present investigation by means of the wake-survey method, and surface pressure-distribution measurements were made by means of flush orifices located in the surfaces of the model. Lift measurements were made by taking the difference between the integrated pressure reaction upon the floor and ceiling of the tunnel (ref. 5). Information as to whether the boundary layer was laminar or turbulent and the location of the region in which turbulence originated were obtained through the use of a medical stethoscope. The end of the stethoscope was attached to a total-head tube which could be projected through the tunnel wall at several locations so that a complete survey of the upper and lower surfaces of the model could be made. A distinct difference between the noise levels associated with laminar and turbulent boundary layers permitted the listener to distinguish very clearly between the two types of flow.

Tests

As previously pointed out, the purpose of the tests was to determine if essentially full-chord laminar flow and net drag savings could be obtained for Reynolds numbers up to about 20.0×10^6. Attempts to obtain full-chord laminar flow were made for Reynolds numbers, which differed by increments of 2.0×10^6 over a range of Reynolds number from 6.0×10^6 to 16.0×10^6 and for Reynolds numbers of 17.0×10^6, 18.0×10^6, and 19.0×10^6. The investigation was made for angles of attack of 0.5°, 1.0°, 1.5°, and 2.0° although the greatest amount of effort was expended for the design lift condition which occurred for an angle of attack of approximately 0.5°.

The procedure followed in attempting to obtain full-chord laminar flow at any particular value of the Reynolds number involved several steps. The model was first carefully inspected and the surfaces rubbed with a clean cloth to remove any apparent disturbances which might cause transition. With the tunnel speed and pressure adjusted for the proper Reynolds number, a stethoscopic survey was then made of the surfaces of the model to determine if full-chord laminar flow existed, and if not, to trace the turbulence back to its origin. In most cases, full-chord laminar flow was not obtained on the first attempt. Sometimes it was found that an adjustment in the suction flow distribution would cure the difficulty. Generally, however, the stethoscopic surveys would indicate one or perhaps several fairly localized regions in which the turbulence was originating. Upon examination of the surface, the disturbance causing the turbulence was sometimes apparent, sometimes not. (A more detailed discussion of the difficulties encountered in maintaining the proper surface condition is contained in a subsequent section of the paper.) In any case, there usually ensued a rather extended period of activity directed toward improving the surface condition. Further surveys with the stethoscope were then made, and in most cases, still more work on the surface was required. Once essentially full-chord laminar flow was obtained, measurements of the wake drag were made at a number of spanwise positions behind the model with the wake-survey equipment. The drag measurements were generally made for a range of total flow coefficients extending from values below that for full-chord laminar flow to values considerably in excess of those required for full-chord laminar flow. In all cases, the flow removal from each slot and the total pressure loss of the suction air in each slot was measured. In addition, measurements of the surface pressure distribution were made for several conditions as was the lift.

CORRECTIONS AND CALCULATIONS

The values of the free-stream dynamic pressure employed in calculating the wake drag, total pressure loss, and suction flow coefficients were corrected for tunnel-wall blockage according to the methods described in reference 5. The surface pressure distributions were corrected for wall effects only through the blocking correction applied to the free-stream dynamic pressure. No further tunnel-wall corrections were applied to the pressure-distribution data since the behavior of the boundary layer is influenced by the actual distribution of pressure and not by a fictitius distribution which would be obtained in free air.

The values of the flow coefficient employed throughout the paper are based on the flow removed through the center group of suction chambers. None of the flow coefficients presented include any of the flow removed through the end chambers.

The total drag coefficients presented are defined as the sum of the wake drag coefficient and the drag coefficient equivalent of the suction power. This method of accounting for the suction power is shown in reference 6 to be valid if, on an actual installation, the efficiency of the internal flow system is equal to that of the main propulsive unit of the aircraft.

RESULTS AND DISCUSSION

The important airfoil-section aerodynamic characteristics to be discussed are the drag, suction-flow and pressure-loss distributions, surface pressure distributions, and lift. Also included is a brief account of some of the difficulties experienced in obtaining the results presented. The drag results will be discussed first.

Drag

Spanwise variation of drag.- The drag data to be presented represent the average of drag values determined at 13 spanwise stations behind the model. The measuring stations were located so that the drag was averaged over a distance of approximately 6 inches on either side of the center line of the model. In order to give some indication of the extent to which the average drag coefficients to be presented are truly representative of two-dimensional flow, a variation of external drag coefficient with spanwise position, which is typical of those obtained in the present investigation, is presented in figure 4. The variation in drag coefficient through the 1-foot spanwise length is seen from this figure to be very small. Rather large variations in drag, however, occurred outside of the 6-inch length measured on either side of the center line. Such variations might have been expected since the length of the slot nearest the trailing edge was only about 15 inches and the survey rake was mounted some 8 inches behind the model.

Drag at angle of attack of 0.5°.- The basic drag results obtained in the investigation are contained in figure 5. The wake drag coefficient, blower drag coefficient, and total drag coefficient are presented as functions of the flow coefficient for various values of the Reynolds number.

Consider first the effect of variations in the flow coefficient on the wake drag coefficient for an angle of attack of 0.5° (fig. 5(a)). All of the wake drag data of figure 5(a) except those for the two highest Reynolds numbers (18.0×10^6 and 19.0×10^6) indicate first a relatively sharp decrease in drag with increasing flow rate after which further increases in flow rate cause little if any reduction in drag. The sharp decrease in wake drag with increasing flow rate indicates a rapid increase in the relative extent of laminar flow. Surveys with the stethoscope indicated that the subsequent leveling off of the curve of wake drag against flow coefficient corresponds to the attainment of essentially full-chord laminar flow. As would be expected, increases in the flow coefficient beyond that value required to achieve nearly full-chord laminar flow cause but little reduction in the drag. The wake drag data for Reynolds numbers of 18.0×10^6 and 19.0×10^6 seem to indicate that a sufficient amount of flow to obtain full-chord laminar flow was not removed. It was found during the tests, however, that increases in the flow coefficient above those values for which drag data are presented at Reynolds numbers of 18.0×10^6 and 19.0×10^6 caused a rapid forward movement of transition so that full-chord laminar flow could not be obtained at these highest Reynolds numbers.

Most of the drag data for Reynolds numbers below 18.0×10^6 indicate the rather significant fact that, although reductions in drag were not obtained as a result of increasing the amount of flow removal beyond a certain relatively short range of C_Q increases in flow removal beyond this range did not cause an increase in wake drag, at least through the range of flow coefficients investigated. This result suggests that there is a rather wide range of flow coefficients through which essentially full-chord laminar flow can be obtained and that the stability of the laminar layer may not be critically dependent upon establishing a particular value of the flow coefficient very closely. This conclusion is not borne out by the results obtained for a Reynolds number of 13.0×10^6. The forward movement of transition indicated to occur at this Reynolds number by the rise in drag with increasing flow coefficient is believed to result from slight imperfections which could possibly have been on the model at the time the data were obtained.

In general, the data of figure 5(a) indicate that the minimum wake drag coefficient is very low in all cases and decreases with increasing Reynolds number. The flow coefficient corresponding to the minimum value of the wake drag coefficient is seen to vary to some extent with Reynolds number; however, these variations are small and rather inconsistent.

The drag coefficient equivalent of the suction power is seen (fig. 5(a)) to vary in a linear manner with flow coefficient for all of the Reynolds numbers. The value of this drag coefficient corresponding to a given flow coefficient is also seen to be relatively independent of Reynolds number.

As would be expected from the data showing the effect of flow coefficient on the wake drag and the drag coefficient equivalent of the suction power, the variation of total drag coefficient $c_{d_o} + c_{d_b}$ with increasing flow coefficient is characterized by a minimum value. It is interesting to note that, in most cases, the flow coefficient corresponding to the minimum total drag coefficient is somewhat smaller than that required to obtain the minimum wake drag coefficient. This, of course, results from the fact that near the flow coefficient for minimum wake drag, the rate of decrease of wake drag with increasing flow is smaller than the corresponding rate of increase of blower drag. The flow coefficient corresponding to the minimum total drag coefficient varies between about 0.0008 and 0.0010 throughout the Reynolds number range.

In order to show more clearly the effect of Reynolds number on the wake drag and total drag, the wake drag coefficient and the total drag coefficient for an angle of attack of 0.5° are plotted as functions of Reynolds number in figure 6. Also shown in figure 6 is the well-known laminar friction drag of a flat plate. The values of the wake drag coefficient are well below those for the flat plate at all Reynolds numbers. The smaller extent of laminar flow obtained at Reynolds numbers of 18×10^6 and 19.0×10^6 is clearly shown by the value of the wake drag obtained at these Reynolds numbers as compared with those obtained at lower Reynolds numbers. The variation of total drag coefficient with

Reynolds number indicates that the total drag of the airfoil is somewhat higher than that for the flat plate at all Reynolds numbers. The smaller extent of laminar flow at the two highest Reynolds numbers is again clearly shown.

Effect of angle of attack.- The data for angles of attack of 1.0°, 1.5°, and 2.0° shown in figures 5(b), 5(c), and 5(d) are, in most cases, not sufficiently extensive to permit detailed discussion of the effect of flow coefficient and Reynolds number. In general, the values of the minimum and total drag coefficients obtained for angles of attack of 1.0°, 1.5°, and 2.0° (figs. 5(b), 5(c), and 5(d), respectively) are of about the same order as those obtained for an angle of attack of 0.5° (fig. 5(a)). The maximum Reynolds number at which essentially full-chord laminar flow was obtained, however, decreased as the angle of attack was increased. The maximum Reynolds numbers at which full-chord laminar flow was obtained were about 16.0×10^6, 13.0×10^6, and 10.0×10^6 for angles of attack of 1.0°, 1.5°, and 2.0°, respectively, as compared to a Reynolds number of about 17.0×10^6 for an angle of attack of 0.5°. These results do not necessarily indicate that essentially full-chord laminar flow could not be obtained at higher Reynolds numbers for the higher angles of attack. The tests of the airfoil at various angles of attack were made toward the end of the investigation and sufficient time was not available to permit the careful attention to surface condition which was found necessary in the tests at an angle of attack of 0.5°. It is, of course, possible that even more careful surface maintenance procedures would be required at the higher angles of attack because of the less favorable pressure gradients over the forward part of the airfoil.

In order to gain some idea of the extent to which the drag was reduced by the use of suction slots, a drag polar for the NACA 66_2-215 airfoil (ref. 7) is presented in figure 7 along with data obtained for the slotted airfoil of the present investigation. The data for the NACA 66_2-215 section are for a Reynolds number of 9.0×10^6 and those for the slotted section are for Reynolds numbers of 8.0×10^6, 13.0×10^6, and 18.0×10^6. It should perhaps be pointed out that, although the airfoil profile employed in the present investigation is not exactly similar to the NACA 66_2-215, the differences are not sufficiently great to influence the comparison shown in figure 7. The data of figure 7 indicate that the drag of the slotted airfoil is about one-half that of the unslotted section in the low drag range of lift coefficients. It is, of course, obvious that the use of slots would result in no appreciable change in the drag for lift coefficients much outside of the low drag range because of the sharp negative pressure peaks and associated adverse gradients near the leading edge.

SUCTION-FLOW AND PRESSURE-LOSS DISTRIBUTION

Measurements of the flow and pressure loss through each slot were made at all test conditions for which data are presented in figure 5. Samples of the flow and pressure-loss data obtained are presented in figures 8 and 9 for Reynolds numbers of 6.0×10^6 and 18.0×10^6. The data are plotted in the form of flow coefficient per slot against chordwise position (fig. 8) and pressure-loss coefficient per slot against chordwise position (fig. 9). The total flow coefficients obtained from integration of the distributions correspond approximately to those required for minimum total drag at the two Reynolds numbers.

A comparison of the suction-flow distributions for Reynolds numbers of 6.0×10^6 and 18.0×10^6 (fig. 9) indicates that a relatively uniform amount of suction through the slots in the favorable gradient (0.4c to 0.6c) was required for the high Reynolds number case as compared with no suction through the first three slots in the favorable gradient for a Reynolds number of 6.0×10^6. Suction was not required in the region of favorable pressure gradient at the lower Reynolds number because a boundary-layer Reynolds number sufficiently high to allow transition was most probably not reached in this region because of the slower rate of growth of the boundary-layer Reynolds number along the surface at the lower-wing Reynolds number. It is perhaps of some significance to point out that it was found unnecessary to seal the front three slots in order to obtain laminar flow at the lower Reynolds number even though no flow was withdrawn through the slots. The ducts leading to the slots were tightly closed, however, so that there was no outflow.

The distribution of flow removal from the position along the surface at which the adverse pressure gradient begins (60 percent chord) to the trailing edge is very similar for the two Reynolds numbers and is characterized by a relatively large increase in flow removal with increasing distance along the surface. The values of the flow coefficient per slot in the region of adverse pressure gradient are, however, somewhat higher for a Reynolds number of 6.0×10^6 than for a Reynolds number of 18.0×10^6.

The distribution of flow removal necessary for angles of attack higher than 0.5° was generally similar in appearance to those obtained at 0.5°. As would be expected, somewhat higher flows were required in the region of favorable gradient on the upper surface at the higher angles of attack. Little difference was noted in the distribution of flow removal over the rear portions of the airfoil at the different angles of attack.

The distribution along the chord of total pressure loss through the slots is seen (fig. 9) to be characterized by a maximum value with essentially no chordwise variation in the region of favorable pressure gradient, followed by a rapid decrease in suction-flow pressure loss in the region of adverse pressure gradient. The reduction of total pressure loss in the region of adverse gradient would be expected since, as the flow progresses through this region, an increasingly large porportion of the total pressure is converted to static pressure along the surfaces of the model outside of the slots. Decreasing the Reynolds number from 18.0×10^6 to 6.0×10^6 is seen to cause some increase in the total pressure loss for all slots. The reason for the small increase in pressure loss at the lower Reynolds number may perhaps be qualitatively explained by the following relation which can be derived easily for simple linear profiles:

$$\left(\frac{\delta_1}{w}\right)^2 \propto \frac{C_Q}{\sqrt{R_x}}$$

for a given chordwise position, where $\frac{\delta_1}{w}$ is the ratio of the height of the sucked layer to the slot width. The data of figure 9 indicate but little difference in the flow coefficients for Reynolds numbers of 6.0×10^6 and 18.0×10^6. The relation above shows that the ratio of the height of the sucked layer to the slot width increases as the Reynolds number is decreased for a constant flow coefficient. Thus, the amount by which the streamtube comprising the sucked flow must be contracted on entering the slot increases as the Reynolds number is decreased. The total pressure loss associated with the flow removal, however, might be expected to increase with increasing values of $\frac{\delta_1}{w}$ because the static pressure of the flow as it entered the slot would be reduced and the viscous losses of the entering flow increased.

SURFACE PRESSURE DISTRIBUTION

The results of measurements of the surface pressure distribution are shown in figure 10 for an angle of attack of 0.5° and Reynolds numbers of 6.0×10^6 and 14.0×10^6, and in figure 11 for a Reynolds number of 7.0×10^6 and angles of attack of 0.5°, 1.0°, 1.5° and 2.0°.

The apparent large Reynolds number effect on the pressure distributions shown in figure 10 is largely the result of a Mach number effect.

Although the free-stream Mach numbers were maintained at relatively low values throughout the investigation, the local Mach numbers were fairly high in some cases. The local Mach numbers corresponding to the peak negative pressure coefficients for Reynolds numbers of 6.0×10^6 and 14.0×10^6 were 0.246 and 0.573, respectively. In general, the pressure-distribution data of figures 10 and 11 are characterized by irregularities which are probably attributable in large measure to surface unfairness, but which may in some degree result from the effects of flow removal. The sharp "jog" in the pressure distribution at approximately 72.5 percent chord is characteristic of the behavior of the surface pressure in the vicinity of a slot. Similar jogs would be expected at the other slots; however, detailed measurements were made at only this one slot position. The actual surface pressure distribution in the region of the slots would therefore appear as a succession of jogs rather than the smooth curve shown in figure 10. Data which show this type of pressure distribution are presented in reference 1. The effect of angle of attack on the pressure distribution (fig. 11) is about as would be expected and warrants no particular comment.

LIFT

In order to provide data from which a portion of the drag polar could be constructed for the airfoil with boundary-layer control, measurements of the lift were made for an angle-of-attack range from -4.0° to $+5.0^\circ$ and for several Reynolds numbers. The measurements were made with the boundary-layer suction in operation. Samples of the lift data obtained are shown in figure 12 for Reynolds numbers of 6.0×10^6 and 9.0×10^6. These data do not appear to warrant any particular comment other than to point out that the higher than design value of the lift coefficient which occurs at an angle of attack of about 0.5° results from the influence of the tunnel-wall boundaries.

DIFFICULTIES ENCOUNTERED IN OBTAINING EXTENSIVE LAMINAR FLOW

Although the low drag coefficients obtained through the use of multiple suction slots are certainly of interest, a proper evaluation of the importance of these results would seem to require some understanding of the practical difficulties encountered in obtaining extensive laminar layers. All through the tests of the present investigation great difficulty was experienced in maintaining the surfaces of the model in such a condition that transition did not occur as a result of some small and oftentimes imperceptible disturbance. As an indication of the extent of these troubles, it seems pertinent to point out that approximately 85 percent of the time required to complete the tests at an angle of attack of 0.5° was spent in working on the surfaces of the model, as compared with the remaining 15 percent of the time, which was spent in running the tunnel. These figures are based on a careful examination of the detailed log which was kept during the time the tests were run.

One of the more tangible forms of disturbance which caused transition was encountered early in the tests. It will be recalled that the model was made in two spanwise sections which were bolted together (fig. 2(a)). The contact surfaces or faces of the fore and aft sections were very carefully machined so that an extremely tight fit was obtained between the two portions of the model. The joint appeared to the unaided eye as a very fine hairline, the presence of which could not be perceived through the sense of feel. Nevertheless, disturbances sufficiently large to cause transition were traced by means of the stethoscope technique to this point. The conclusion was reached that, in spite of the tight fit, a small but sufficient amount of air to cause transition must be passing from the inside of the model through the joint to the outside surface. After very carefully glazing over the joint with lacquer-base putty, transition could no longer be traced to this source. It was then found that the region of laminar flow was limited to relatively small extents by disturbances which originated in the vicinity of the surface pressure measuring orifices in the front part of the model. These pressure orifices were formed by drilling a small hole through a length of threaded brass stock which was then screwed into a tapped hole in the surface. The end of the brass rod was, of course, very carefully faired into the surface contour. Again, it was concluded that a small amount of air passing through the threaded joint was causing the difficulty, and again, the trouble was cured by carefully glazing over the joint. These difficulties were first encountered in attempting to increase the Reynolds number for full-chord laminar flow above about 11.0×10^6. After glazing the joints between the two halves of the model and around the pressure orifices, the Reynolds number for full-chord laminar flow was immediately increased from 11.0×10^6 to about 16.0×10^6. Leakage through the joints, however, continued to cause some trouble throughout the remainder of the investigation because of the difficulty of maintaining a satisfactory seal with a tissue-thin film of glazing putty.

The occurrence of transition on the surfaces of the model could frequently be traced to small pieces of lint left by a polishing cloth, and to small particles of dirt. Removal of these disturbances generally alleviated the difficulty. Transition was observed to occur in one instance as a result of another type of disturbance. A small though rather noisy blowdown type of wind tunnel is located in the general vicinity of the low-turbulence pressure tunnel. No physical connection exists between the two tunnels although a relatively high-frequency noise, sufficiently loud to be somewhat annoying, is clearly heard in the test section of the low-turbulence pressure tunnel when the blowdown tunnel is operated. A sudden increase in the drag of the slotted model was observed to coincide with the beginning of a run in the blowdown tunnel, and a sudden decrease in the drag was found to correspond to the end of the run in the blowdown tunnel. These observations were interpreted as meaning that the noise of the blowdown tunnel caused a forward movement of the transition point.

In many instances transition was observed to occur far forward on the airfoil surfaces even though no perceptible disturbance could be found, but further rubbing and polishing of the surface restored the extent of laminar flow. Early in the tests the entire forward portion of the model was glazed and carefully faired and sanded so as to eliminate any possible harmful effect of a number of very small blow holes in the surface. These holes were perhaps 0.01 inch in diameter. Frequent sanding and polishing of the glazed surface were found to be necessary, and the entire forward portion of the model was sanded to bare metal, reglazed and refinished on three separate occasions. Partial refinishing was required on a number of occasions. Most of this effort was expended not in any attempt to improve an obviously bad surface condition or to remove some obvious disturbance, but rather, in the hope that the rubbing, polishing, or sanding would eliminate the trouble whatever its source might be. Although such a procedure represents a rather blind or random approach, there seemed to be no alternative and it was quite effective in many instances. It might be pointed out that similar procedures have been employed for many years in attempting to obtain extensive laminar layers at Reynolds numbers above 6.0×10^6 to 9.0×10^6 on NACA 6-series airfoil sections without boundary-layer control.

The wind-tunnel experience obtained in the present investigation indicates that the use of suction slots does not materially reduce the sensitivity of the laminar layer to minute surface imperfections. The difficulties to be encountered in attempting to obtain extensive laminar layers on aircraft through the use of multiple suction slots would seem, therefore, to be at least as great as the difficulties encountered in attempting to obtain extensive laminar layers on airplane wings employing low-drag type of airfoils without boundary-layer control. This and the preceding discussion should not be construed as implying that extensive laminar layers cannot be obtained on practical operational aircraft, but rather, is intended to emphasize the degree of excellence of surface condition that is required. The question of whether the construction and mainenance of such a surface is practical must ultimately be answered by the manufacturer and operator.

CONCLUSIONS

An experimental investigation of a 15-percent-chord thick low-drag type of airfoil section equipped with a suction slot arrangement designed to maintain full-chord laminar flow at a Reynolds number of 20.0×10^6 indicated the following conclusions:

1. Essentially full-chord laminar flow with accompanying total drag coefficients of about 0.0012 can be maintained through the use of multiple suction slots on a carefully constructed and maintained wind-tunnel model for Reynolds numbers of as high as 16.0×10^6 to 17.0×10^6.

2. Small particles of lint, noise, and minute flows of air into the boundary layer through machined joints in the surface caused large forward movements of the transition point. In many instances transition occurred at forward positions even though no perceptible disturbance was found, but further rubbing and polishing of the surface restored the extent of laminar flow.

3. The degree of surface excellence required in attempting to obtain extensive laminar layers on aircraft through the use of multiple slots would seem to be at least as high as that found necessary in the past in attempting to obtain extensive laminar flows on airplane wings employing low-drag type of airfoil sections without boundary-layer control.

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TABLE I

ORDINATES FOR THE NACA 66_2-(1.8)15 (a = 0.6) MODIFIED AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.40	1.133	.40	.888
.60	1.342	.60	1.092
1.00	1.680	1.00	1.370
1.25	1.850	1.25	1.500
2.50	2.517	2.50	2.013
5.00	3.523	5.00	2.758
7.50	4.317	7.50	3.317
10.00	4.982	10.00	3.813
15.00	6.077	15.00	4.578
20.00	6.925	20.00	5.157
25.00	7.582	25.00	5.592
30.00	8.072	30.00	5.908
35.00	8.413	35.00	6.125
40.00	8.618	40.00	6.252
45.00	8.695	45.00	6.295
50.00	8.645	50.00	6.250
55.00	8.443	55.00	6.090
60.00	8.045	60.00	5.773
65.00	7.400	65.00	5.275
70.00	6.510	70.00	4.622
75.00	5.455	75.00	3.862
80.00	4.318	80.00	3.050
85.00	3.173	85.00	2.233
90.00	2.027	90.00	1.410
95.00	.872	95.00	.592
96.00	.648	96.00	.435
97.00	.440	97.00	.295
98.00	.253	98.00	.173
99.00	.102	99.00	.073
100.00	0	100.00	0

L. E. radius: 1.433
Slope of radius through L.E.: 0.0987

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TABLE II

SLOT DATA

[All dimensions in percent airfoil chord]

Chordwise location	Nozzle diameter	Measuring region span	Slot width
Upper surface			
41.000	0.328	26.28	0.0050 to 0.0067
46.000	.328	25.34	0.0050 to 0.0067
51.267	.328	24.30	0.0050 to 0.0067
55.667	.328	23.34	0.0050 to 0.0067
60.000	.328	22.51	0.0050 to 0.0067
63.900	.525	21.76	0.0125
66.800	.525	21.15	0.0125
69.800	.525	20.52	0.0108
72.717	.525	19.92	0.0108
75.750	.525	19.30	0.0117
78.700	.525	18.72	0.0108
81.483	.525	18.10	0.0125 to 0.0133
85.100	.525	17.52	0.0117
87.917	.525	16.93	0.0125
90.883	.525	16.32	0.0117
93.733	.525	15.73	0.0133
96.783	.525	15.14	0.0158 to 0.0167
Lower surface			
40.000	0.328	26.57	0.0067
47.000	.328	25.11	.0075
53.417	.328	23.85	.0067
59.400	.328	22.68	.0067
64.133	.525	21.70	.0133
68.150	.525	20.88	.0133
71.917	.525	20.08	.0133
75.900	.525	19.27	.0117
79.600	.525	18.52	.0125
83.683	.525	17.72	.0150
87.700	.525	16.90	.0150
91.633	.525	16.12	.0150
95.600	.525	15.34	.0233

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TABLE III

PRESSURE-DISTRIBUTION ORIFICE LOCATIONS

[All dimensions in percent airfoil chord]

Upper-surface stations	Lower-surface stations
0.	0.067
.083	.300
.200	.867
.916	2.500
2.100	4.600
3.242	6.833
5.250	10.867
7.450	14.867
9.750	19.767
13.067	25.000
16.816	30.167
21.650	36.258
26.517	41.267
30.700	45.633
33.867	50.283
37.100	56.300
39.550	61.734
43.517	66.200
48.800	70.083
53.417	73.967
57.800	77.833
62.000	81.700
65.417	85.700
68.383	89.517
71.317	93.833
71.900	
72.283	
72.517	
73.033	
73.317	
73.817	
74.683	
77.267	
80.183	
83.283	
86.500	
89.517	
92.250	
95.200	

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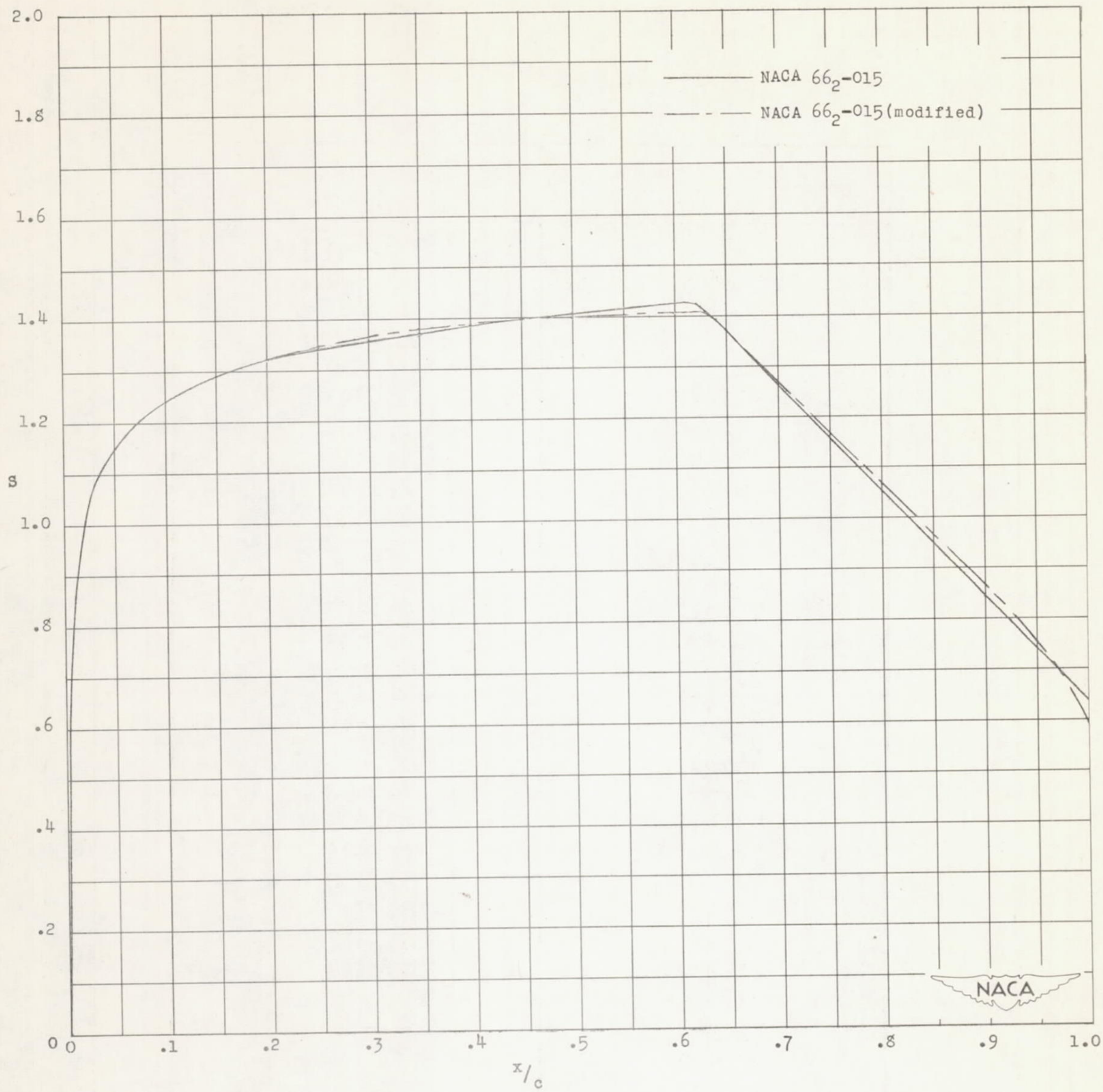
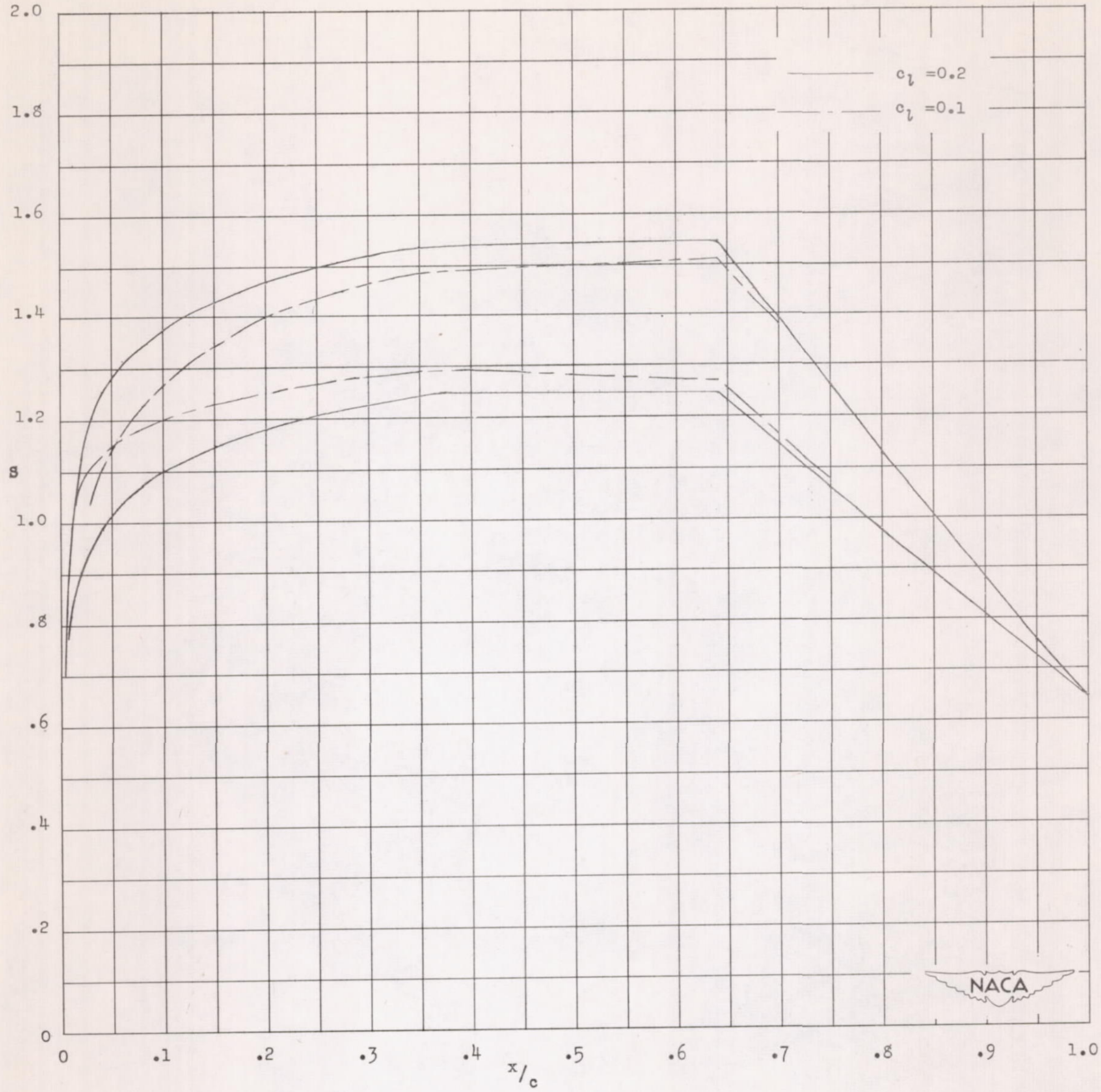


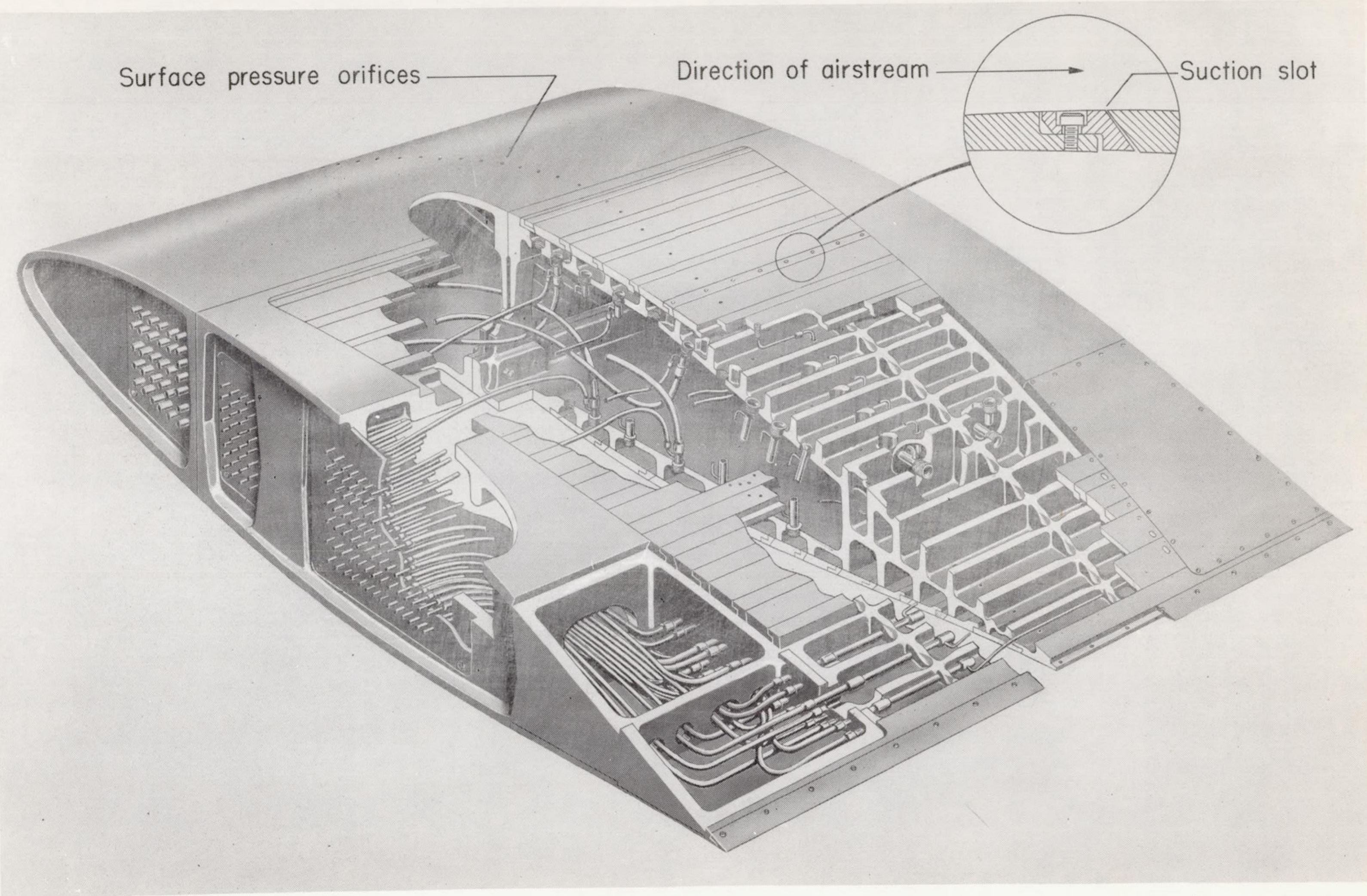
(a) Without camber $c_l = 0$.

Figure 1.- Theoretical pressure distributions of an NACA 66-series airfoil of 15-percent-chord thickness with and without camber.



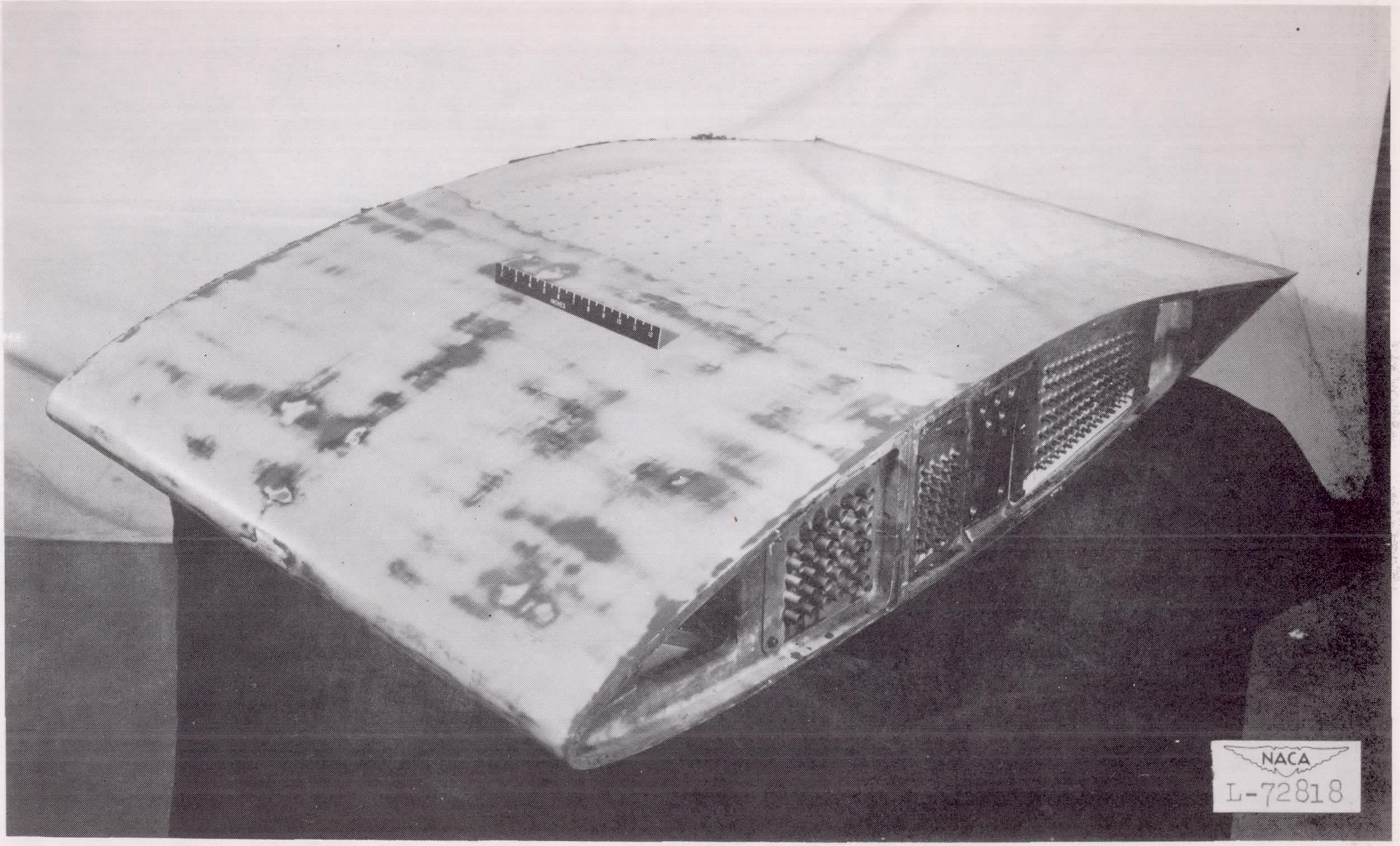
(b) NACA 66_2-015 (modified) cambered to $c_l = 0.18$.

Figure 1.- Concluded.



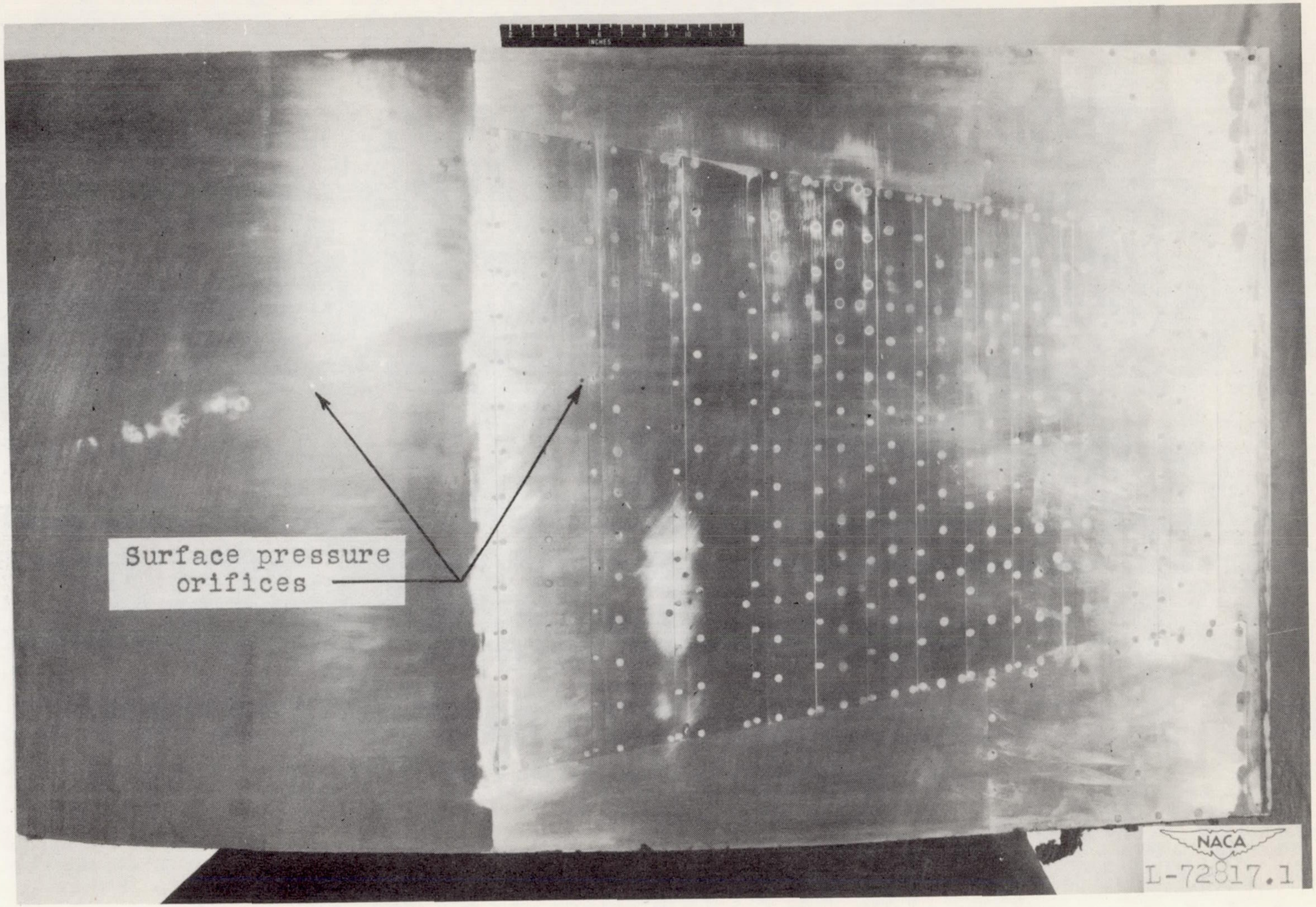
(a) Cutaway diagram showing details of model.

Figure 2.- Diagram and photographs of the boundary-layer suction model having a thickness of 15 percent.



(b) Three-quarter front view of model.

Figure 2.- Continued.



(c) Bottom-surface view of model.

Figure 2.- Concluded.

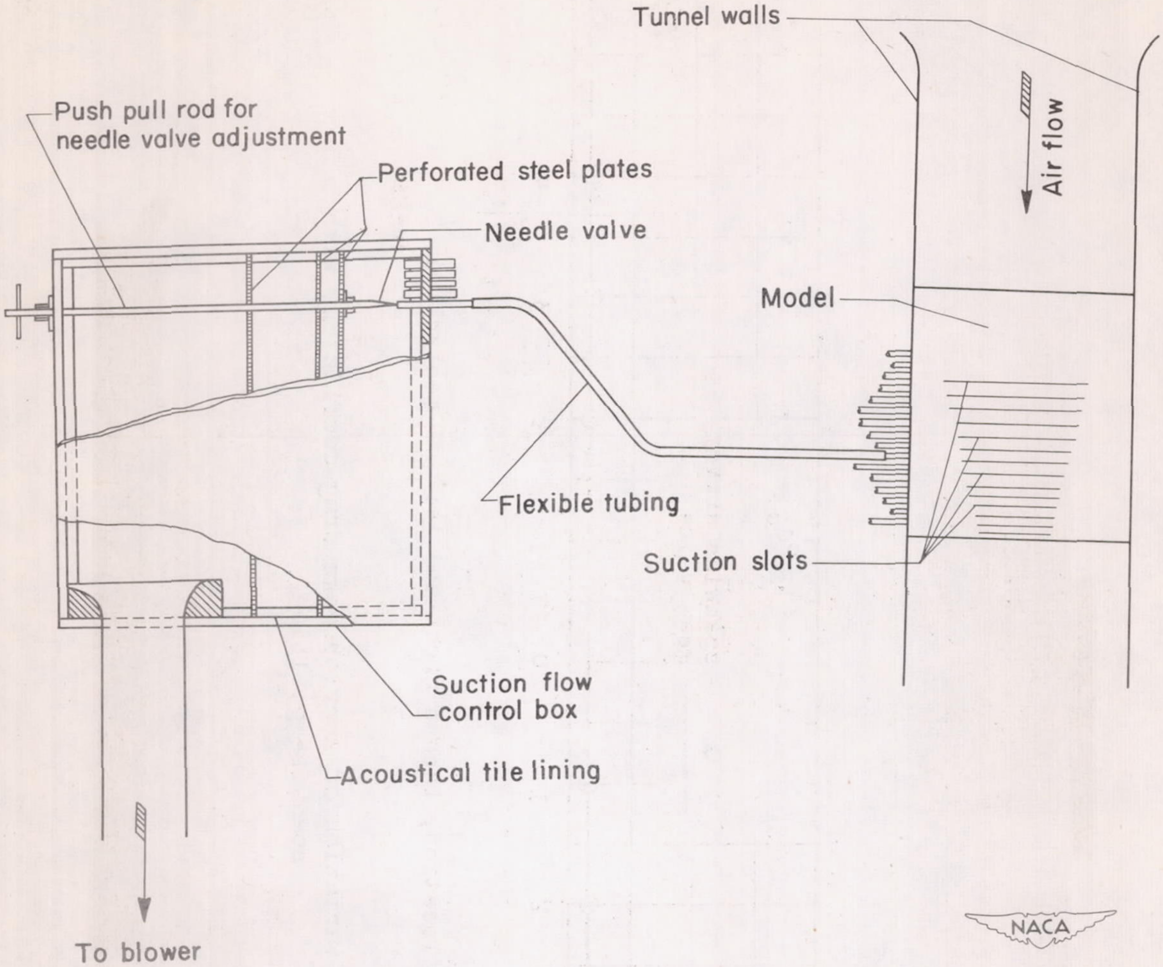


Figure 3.- Schematic drawing showing the method of controlling the flow through each slot in the model by means of needle valves in the suction-flow control box.

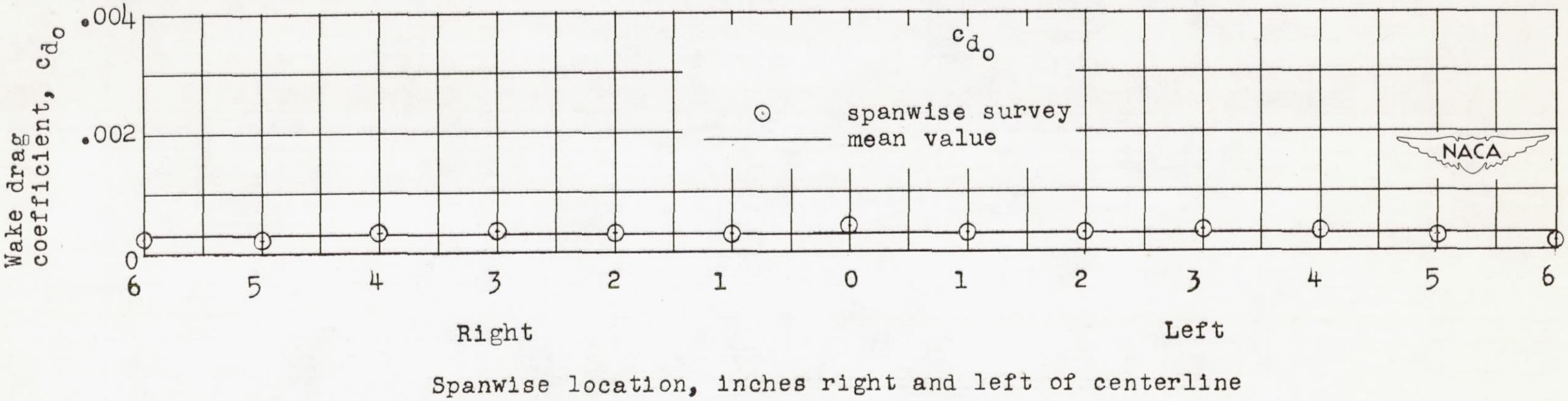
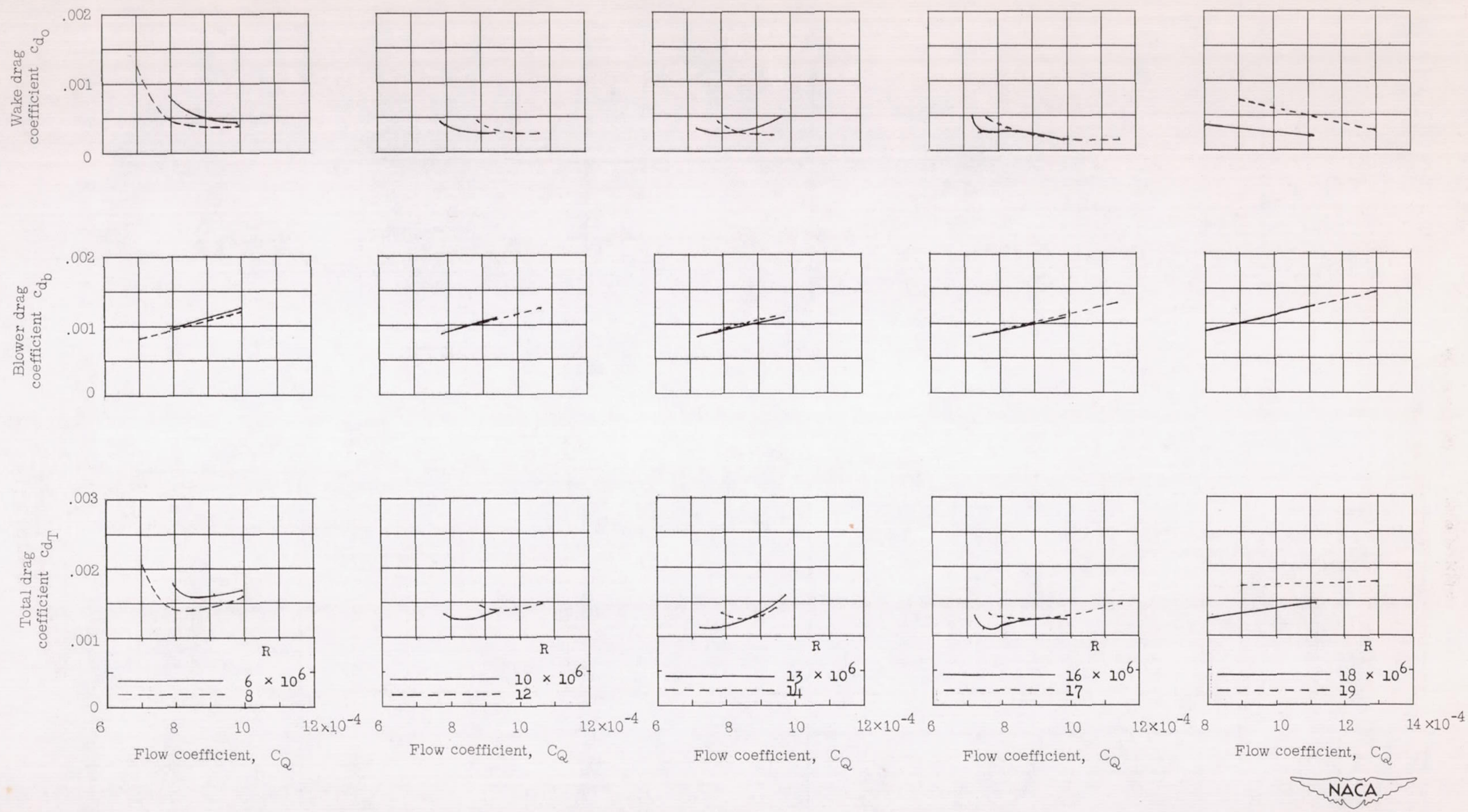
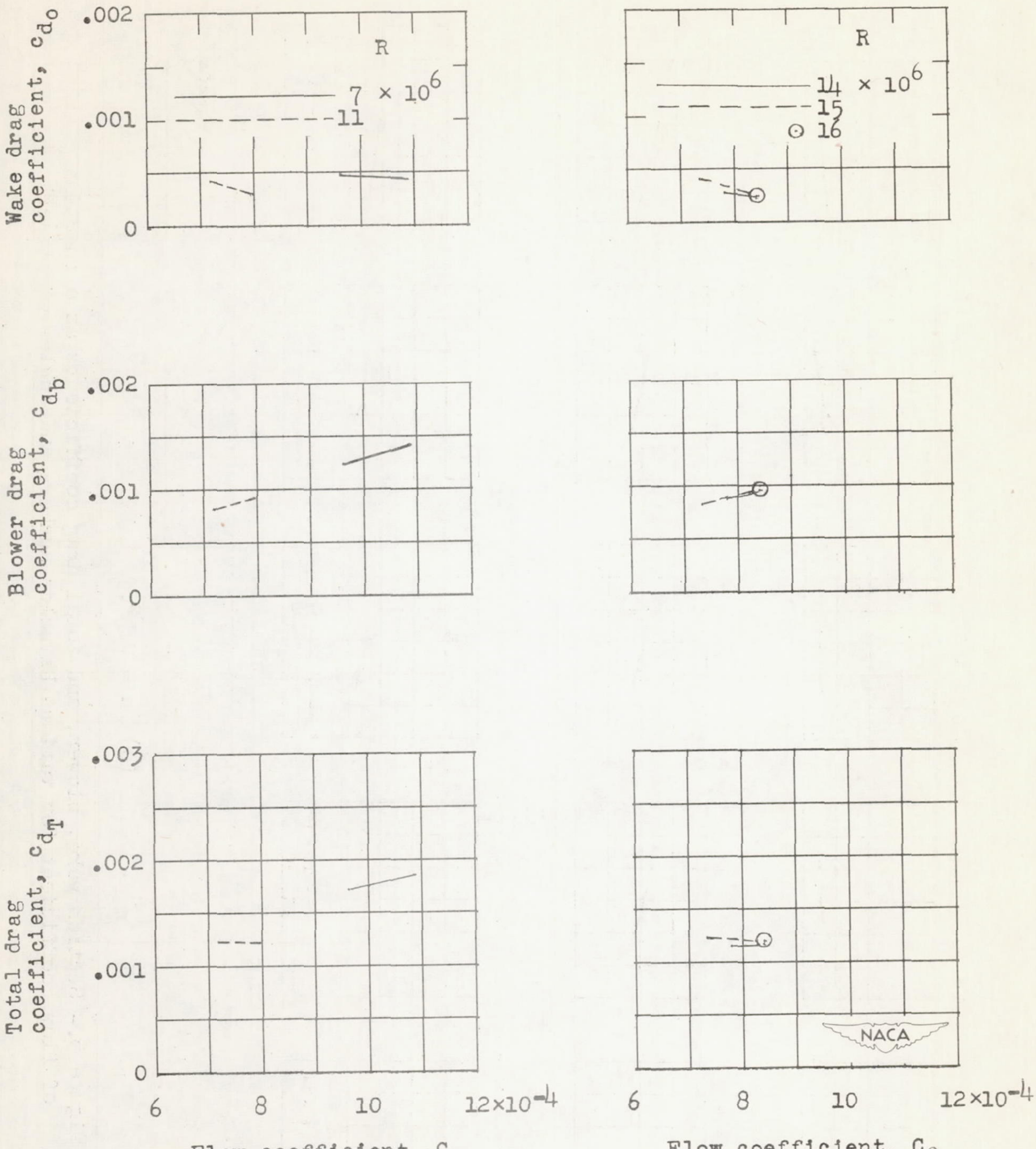


Figure 4.- Typical variation of section wake drag coefficient with spanwise position.



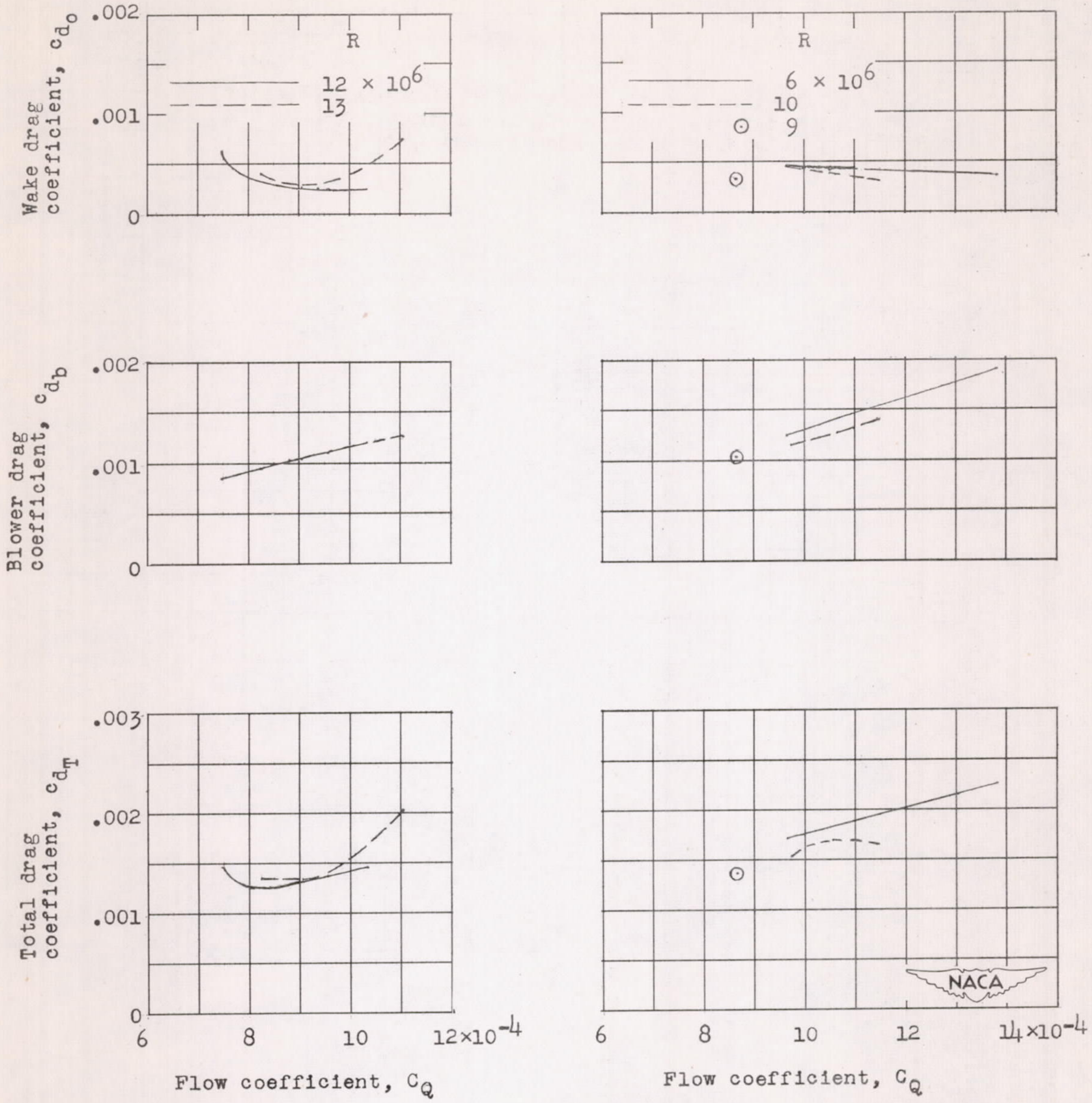
(a) $\alpha = 0.5^{\circ}$.

Figure 5.- Section wake, blower, and total drag coefficients as a function of flow coefficient for various Reynolds numbers and angles of attack.



(b) $\alpha = 1.0^\circ$.

Figure 5.- Continued.



(c) $\alpha = 1.5^{\circ}$.

(d) $\alpha = 2.0^{\circ}$.

Figure 5.- Concluded.

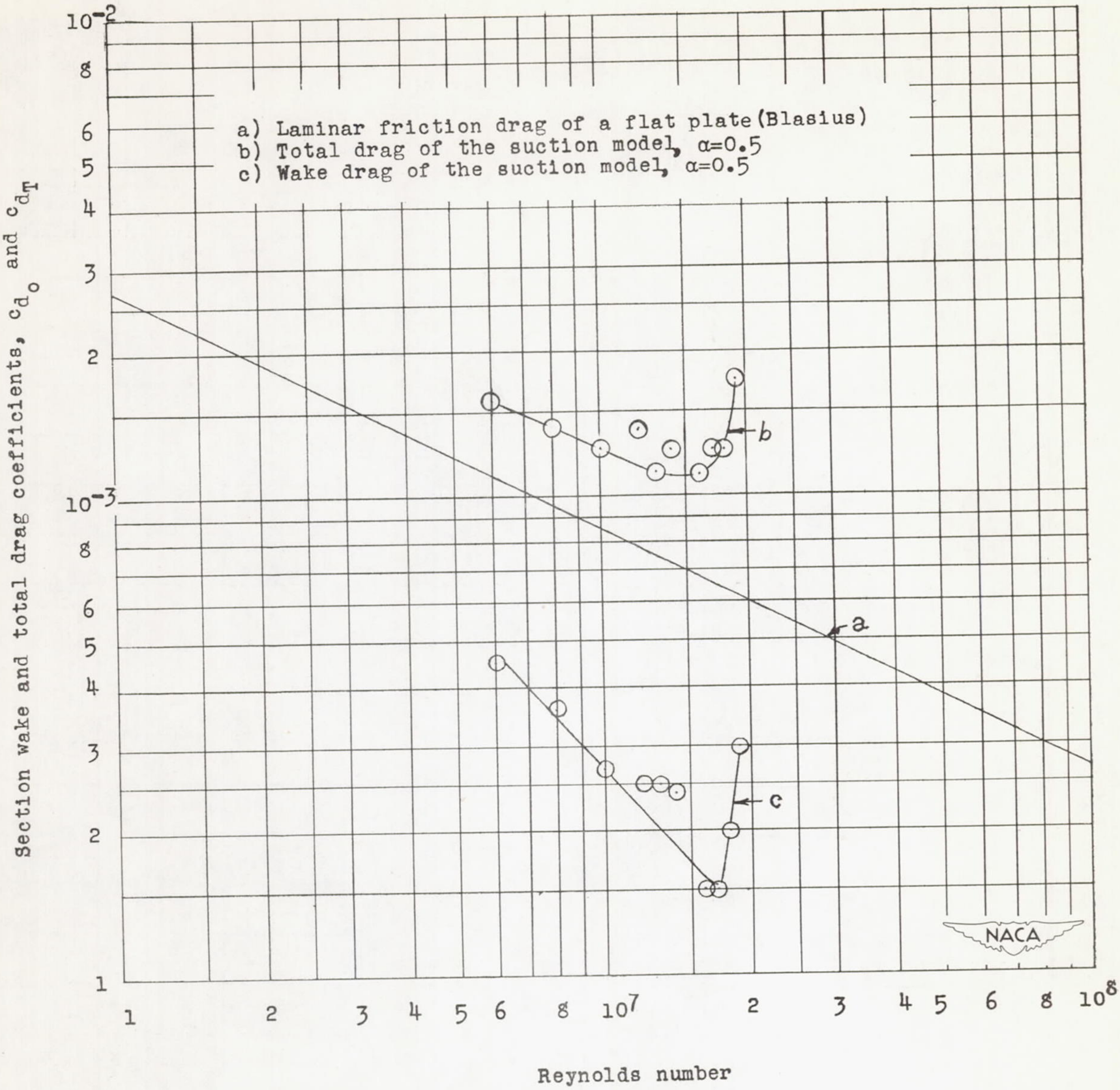


Figure 6.- Variation of section wake and total drag coefficient with Reynolds number for the boundary-layer suction model having a thickness of 15 percent chord in comparison with the laminar friction drag of a flat plate.

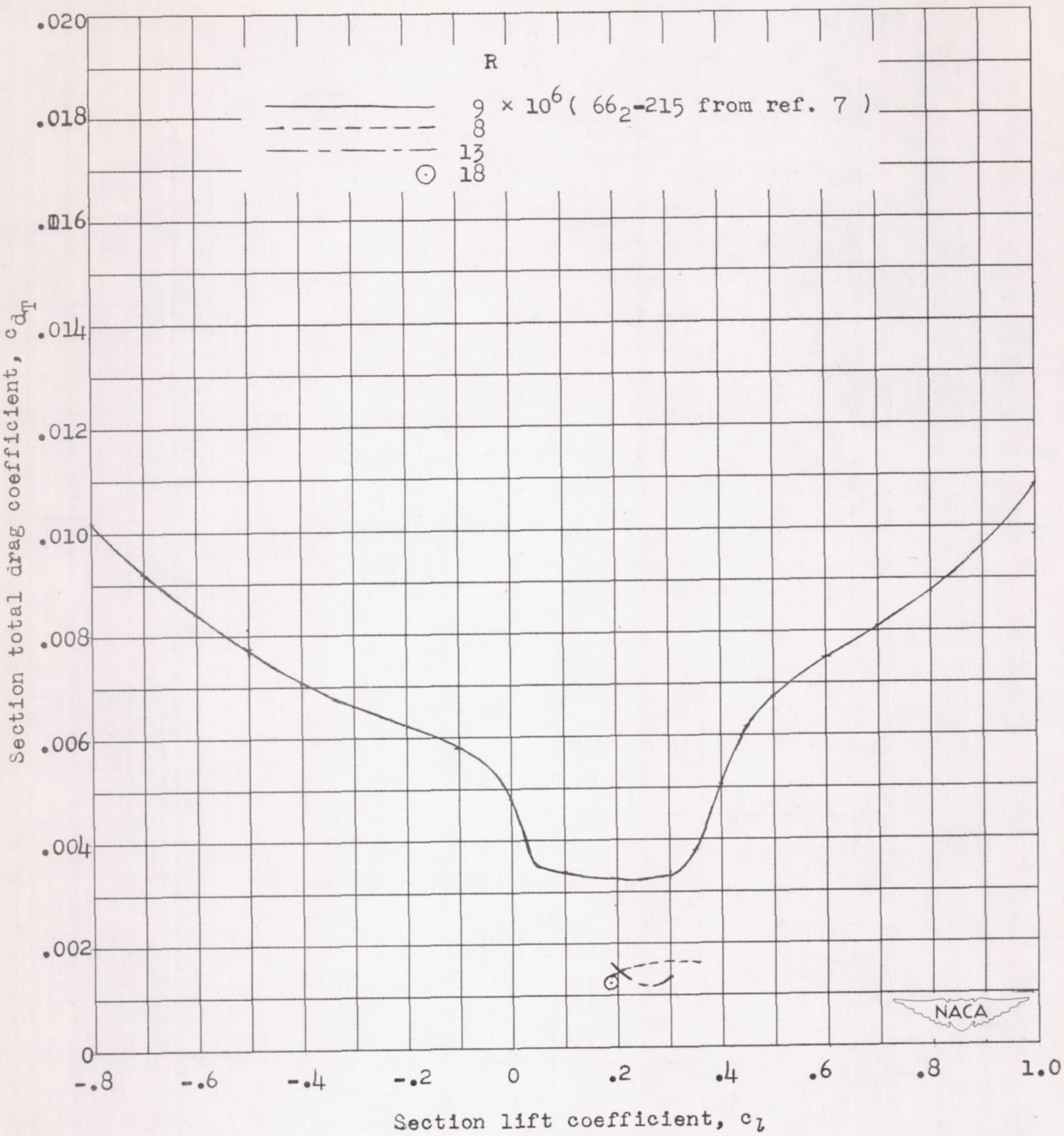


Figure 7.- Comparison of drag polars for the 15-percent-thick-chord boundary-layer suction model and for the NACA 66_2-215 airfoil section (ref. 7) without boundary-layer suction.

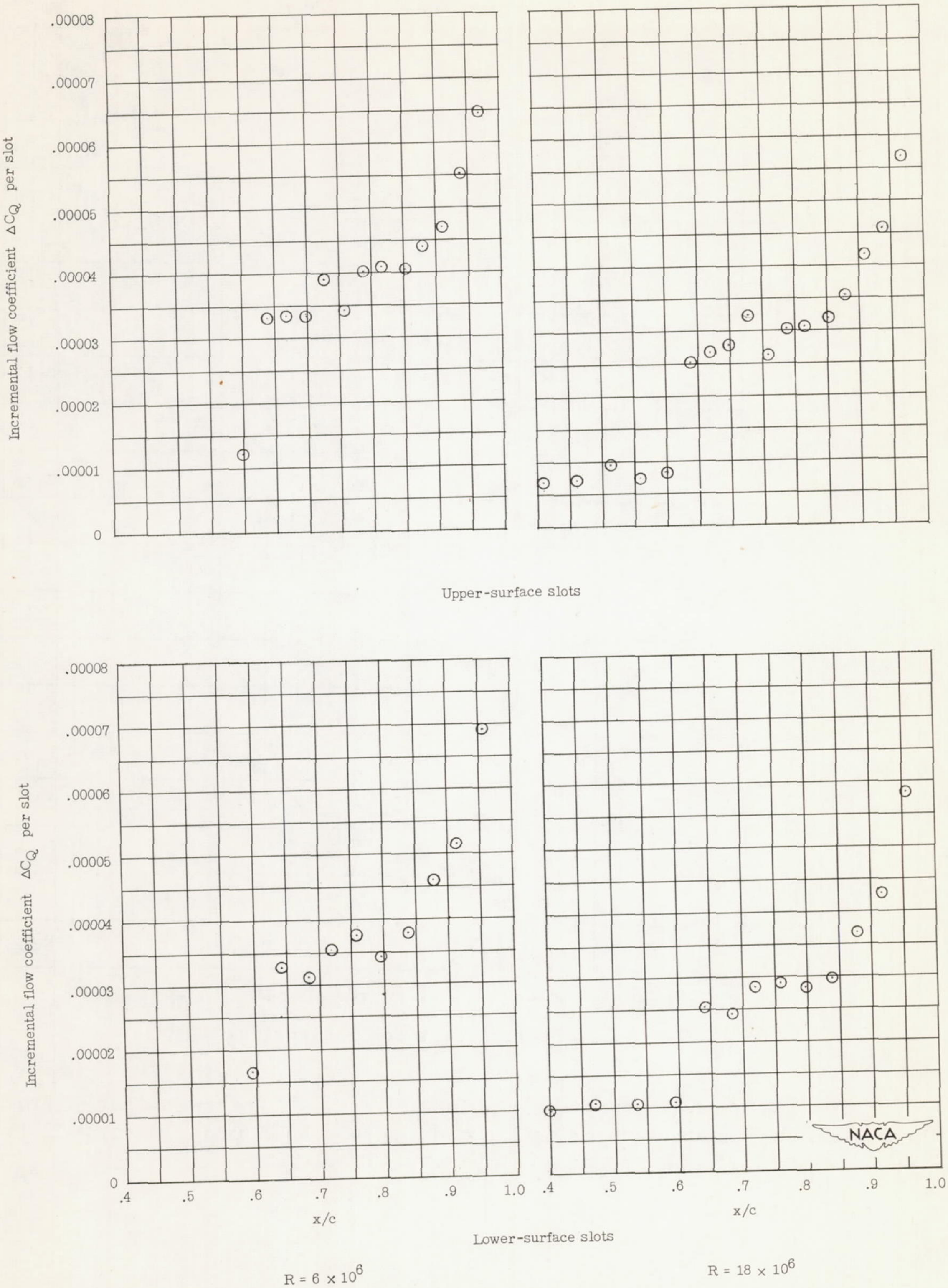


Figure 8.- Comparison of the flow coefficient distribution for two Reynolds numbers. $\alpha = 0.5^{\circ}$.

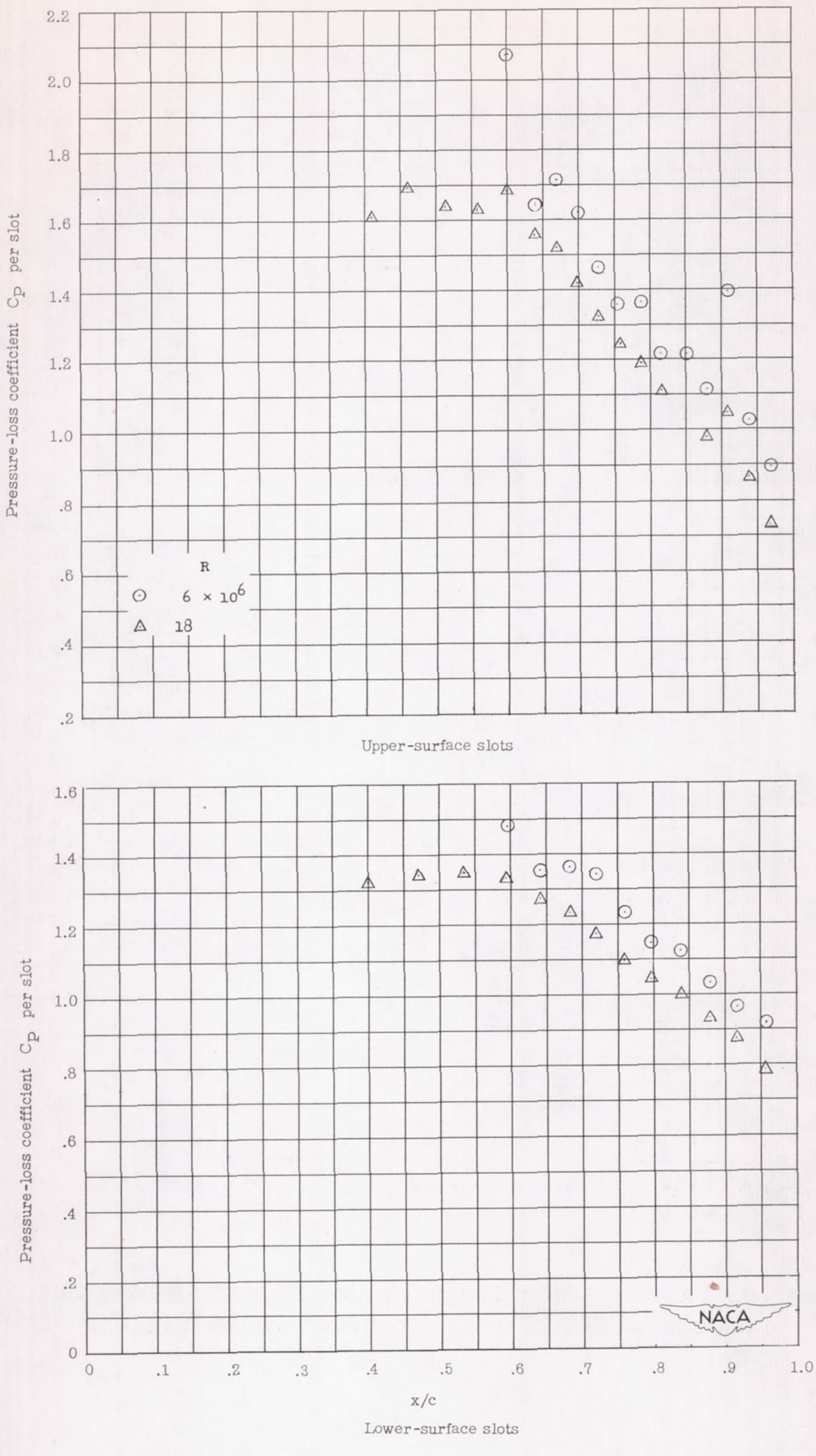


Figure 9.- Chordwise variation of pressure-loss coefficient for two Reynolds numbers. $\alpha = 0.5^{\circ}$.

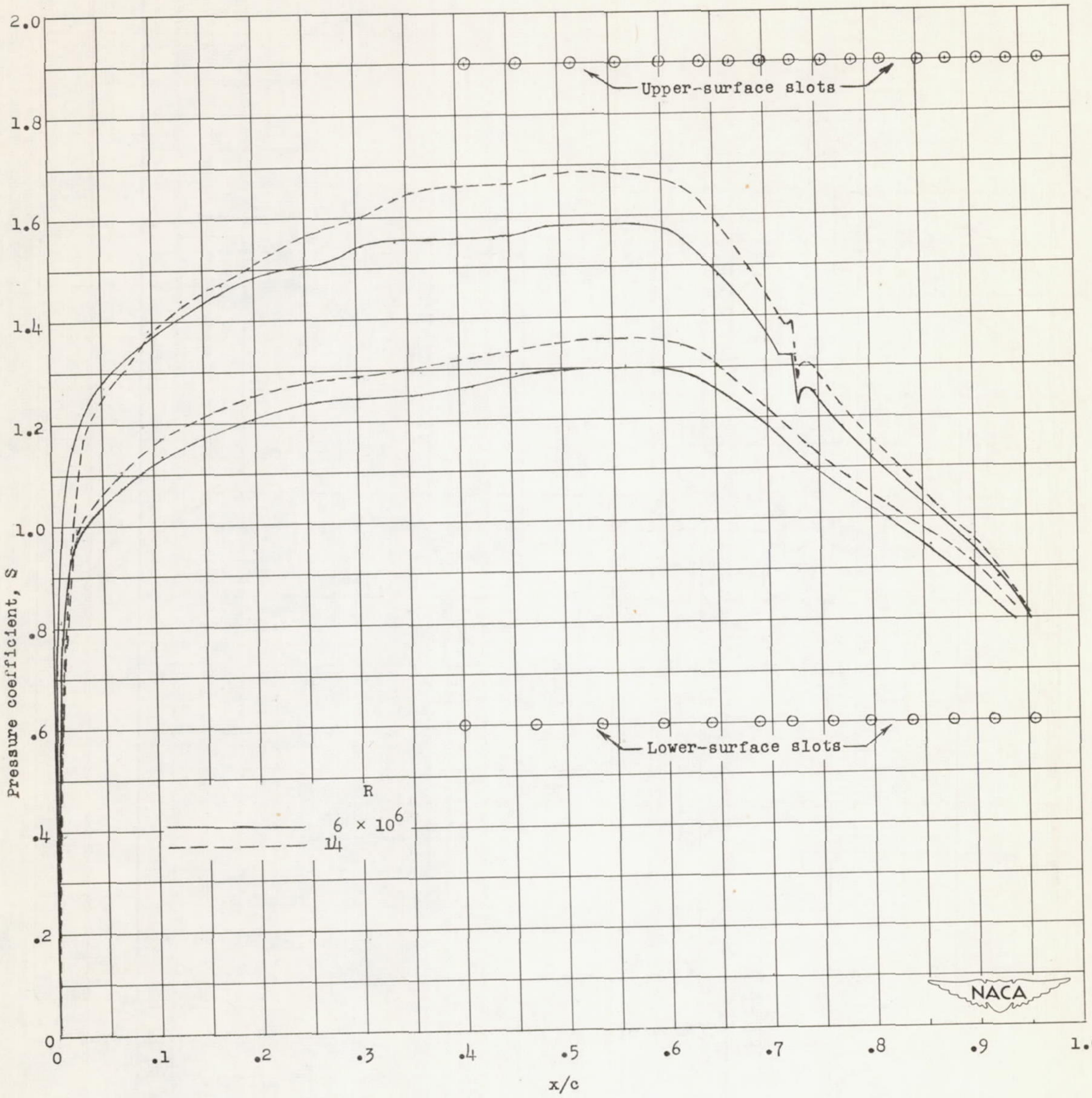


Figure 10.- Airfoil-section pressure distributions for two Reynolds numbers with all suction slots in operation. $\alpha = 0.5^\circ$.

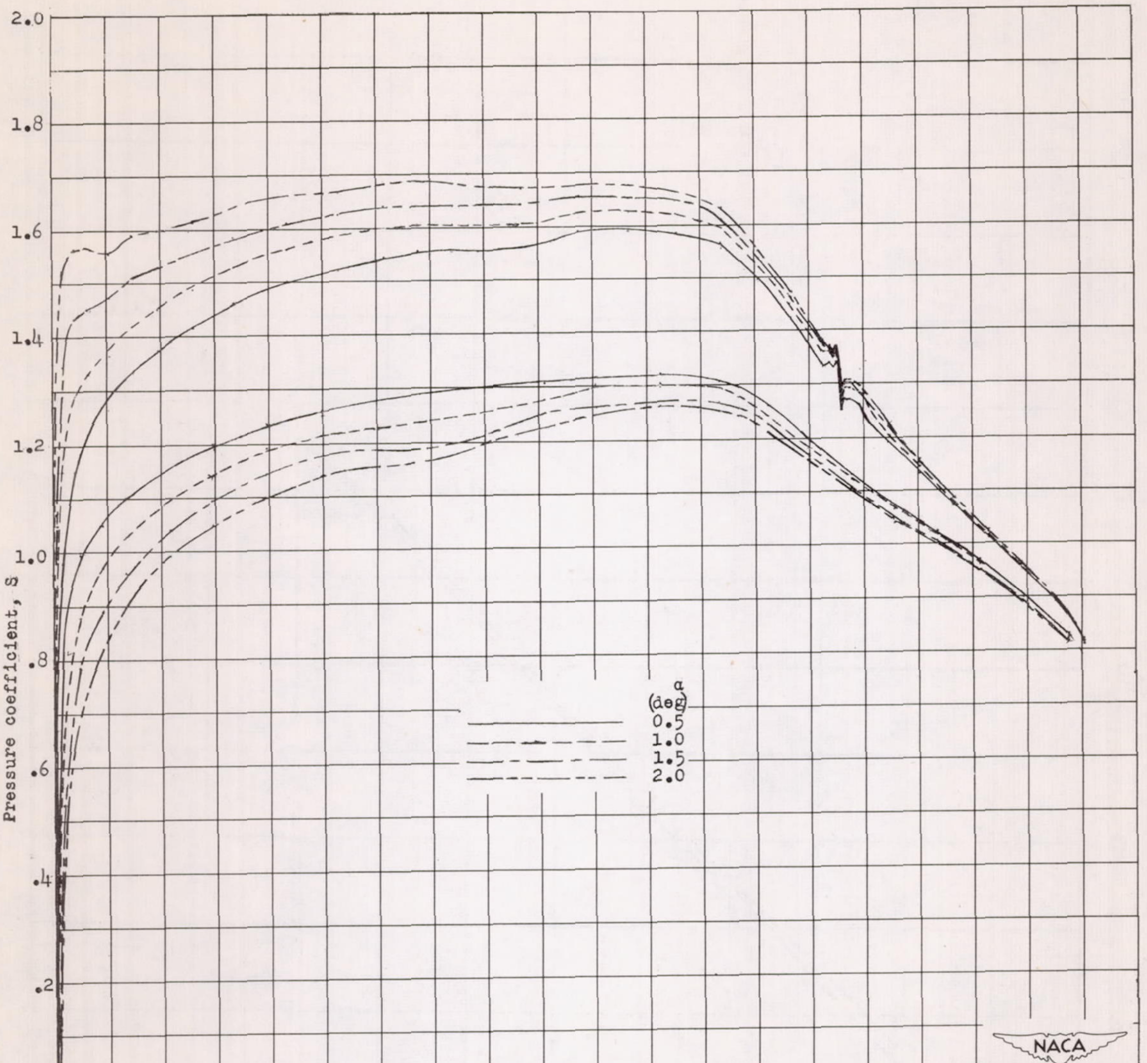


Figure 11.- Airfoil-section pressure distribution for various angles of attack with all suction slots in operation. $\alpha = 0.5^{\circ}$.

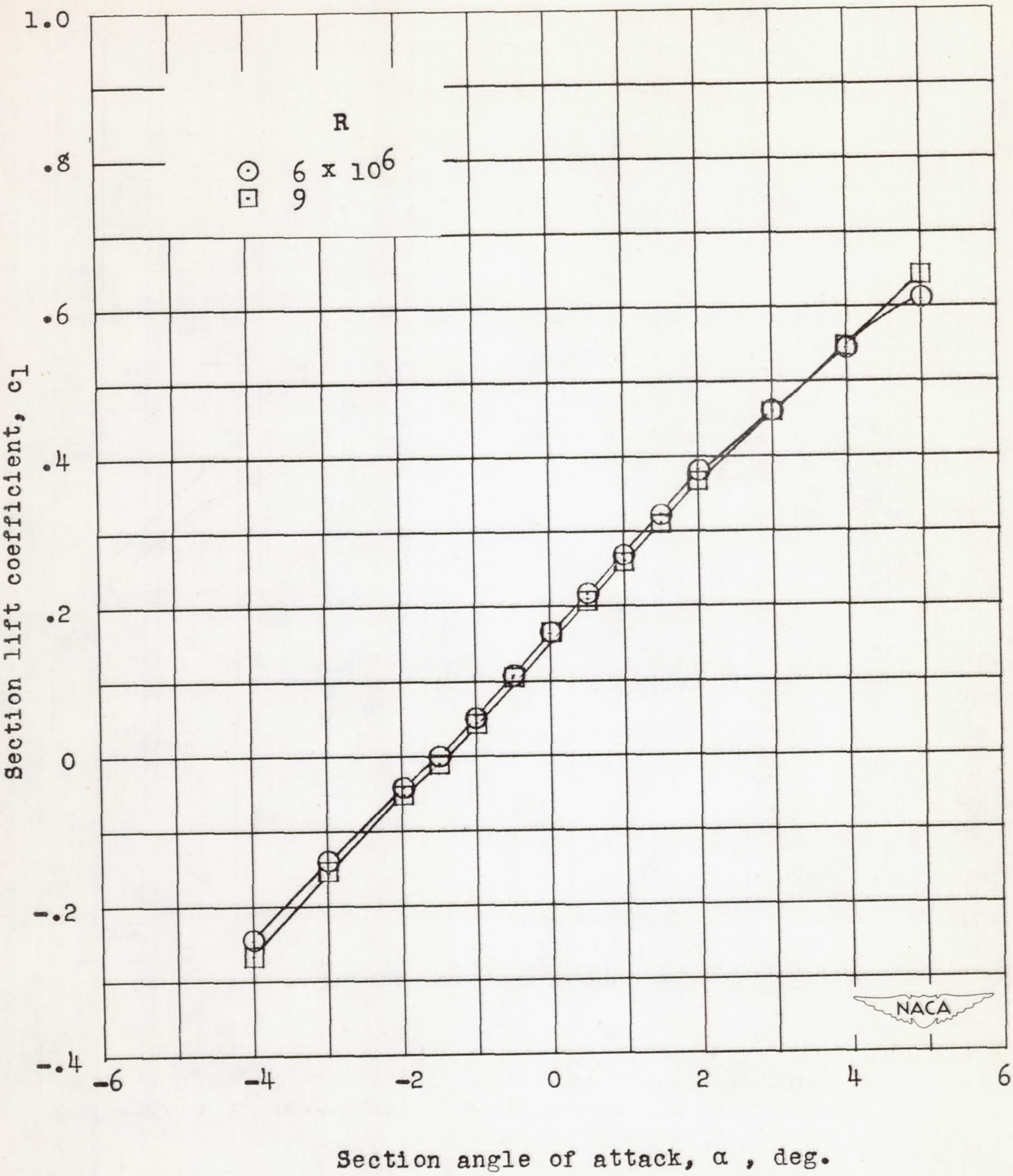


Figure 12.- Section lift coefficients as a function of angle of attack for two Reynolds numbers.