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TECHNICAL NOTE 2112

FURTHER EXPERIMENTAL STUDIES OF AREA SUCTION FOR THE CONTROL OF THE LAMINAR BOUNDARY LAYER ON A POROUS BRONZE NACA 64A010 AIRFOIL

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FURTHER EXPERIMENTAL STUDIES OF AREA SUCTION FOR THE CONTROL OF THE LAMINAR BOUNDARY LAYER ON A POROUS BRONZE NACA 64A010 AIRFOIL

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SUMMARY

A low-turbulence wind-tunnel investigation was made of an NACA 64A010 airfoil having a porous surface to determine the reduction in section total-drag coefficient that might be obtained at large Reynolds numbers by the use of area suction. Initial results of this investigation have been reported previously. The present paper presents the results of additional tests of the same airfoil model equipped with a porous skin of lower porosity.

Full-chord laminar flow was maintained by application of area suction up to a Reynolds number of approximately 20×10^6. At this Reynolds number, combined wake and suction drags of the order of 38 percent of the drag for a smooth and fair NACA 64A010 airfoil without boundary-layer control were obtained. It seems likely from the results that attainment of full-chord laminar flow by means of continuous suction through a porous surface will not be precluded by a further increase in Reynolds number provided that the airfoil surfaces are maintained sufficiently smooth and fair and provided that outflow of air through the surface is prevented.

INTRODUCTION

A recent two-dimensional wind-tunnel investigation of area suction applied to an NACA 64A010 airfoil (reference 1) indicated that full-chord laminar flow could be obtained at Reynolds numbers at least up to approximately 8×10^6. The resultant total-drag coefficients (wake drag plus the drag equivalent of the suction power required) were lower than the drag for the NACA 64A010 airfoil without boundary-layer control. An increasingly nonuniform chordwise distribution of inflow occurred with an increase in Reynolds number because of the high porosity of the porous bronze skin. (See reference 1.) Excessive suction-flow rates were required, therefore, to prevent boundary-layer transition caused

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by outflow of air through the airfoil surface; the excessive suction flows resulted in no reduction in total drag at Reynolds numbers greater than approximately 8×10^6.

In an attempt to improve the chordwise inflow distribution and thus obtain full-chord laminar flow and reductions in total drag at larger values of the Reynolds number, the same airfoil model used in the original investigation (reference 1) has been retested with a porous sintered-bronze surface of much lower porosity. The investigation was made in the Langley two-dimensional low-turbulence pressure tunnel at Reynolds numbers up to approximately 20×10^6. Wake-drag coefficients, suction-flow coefficients, and suction-air pressure-loss coefficients were measured.

SYMBOLS AND COEFFICIENTS

α_o	section angle of attack
c	airfoil chord
b	span of porous surface
ρ_o	free-stream density
U_o	free-stream velocity
q_o	free-stream dynamic pressure $\left(\frac{1}{2}\rho_o {U_o}^2\right)$
Q	total quantity rate of flow through both airfoil surfaces
C_Q	suction-flow coefficient (Q/bcU_o)
H_o	free-stream total pressure
H_i	total pressure in model interior
p	local static pressure on airfoil surface
S	airfoil pressure coefficient $\left(\frac{H_o - p}{q_o}\right)$
R	free-stream Reynolds number based on airfoil chord
C_P	suction-air pressure-loss coefficient $\left(\frac{H_o - H_i}{q_o}\right)$

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c_{d_w}	section wake-drag coefficient
c_{d_s}	section suction-drag coefficient $(C_Q C_P)$
c_{d_T}	section total-drag coefficient $\left(c_{d_s} + c_{d_w}\right)$
v_o	velocity through airfoil surface
Δp	static-pressure drop across porous surface
μ	absolute viscosity
t	thickness of porous material
c_{v_o}	porosity factor, $(\text{length})^2$ $\left(\left\lvert\frac{v_o}{\Delta p}\right\rvert \mu t\right)$

MODEL AND TESTS

The model tested was essentially the same NACA 64A010 model described in detail in reference 1 (uncompartmented configuration), with the exception that a new lower-porosity skin was used. Ordinates of the NACA 64A010 airfoil are presented in reference 2.

The sintered-bronze skin used was approximately 0.090-inch thick and was fabricated of spherical bronze particles which were small enough to pass through a 400-mesh screen. The normal velocity through the bronze material varied directly with pressure drop across the material. The measured porosity of the skin was such that, with air at atmospheric conditions, an applied pressure drop of 1.4 pounds per square inch induced a velocity of 0.38 foot per second through the skin. These values correspond to a porosity factor c_{v_o} equal to 0.0525×10^{-10} foot^2 as compared with a value of 1.44×10^{-10} foot^2 for the original sintered-bronze material used for the tests of reference 1. The significance of the porosity factor c_{v_o} is discussed in more detail in appendix A of reference 1.

Two sheets of sintered bronze 13 inches wide were used to form the center part of the airfoil surfaces from the trailing edge to the 2-percent-chord station. The skin was fastened along the spanwise edges to $\frac{1}{2}$-inch inner end plates; consequently, a 12-inch span of skin was left open to suction. A sheet of duralumin was formed around the leading-edge contour and butted to the bronze. The leading edge was glazed and faired with hard-drying putty up to the 5-percent-chord

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station, which is approximately the chordwise station ahead of which no suction is required theoretically to maintain the boundary-layer Reynolds number less than the critical value for all test Reynolds numbers anticipated (reference 1).

The tests were made in the Langley two-dimensional low-turbulence pressure tunnel and consisted of wake-drag, suction-flow, and suction-air pressure-loss measurements obtained by the methods described in references 1 and 3. The tests were made with the model at zero angle of attack at Reynolds numbers of 5.9×10^6, 12.0×10^6, 15.0×10^6, and 19.8×10^6. The Mach number for all tests was less than 0.2.

RESULTS AND DISCUSSION

Wake drag.- Spanwise surveys of section wake-drag coefficient over the part of the model covered with the porous skin indicated appreciable variations in wake drag. Examples of these variations are shown in figure 1. The large variations, occurring only over the outer portions of the bronze skin, were due to disturbances originating at or near the junctures between the bronze skin and the solid model end sections; over a spanwise region of 3 to 4 inches at the center of the bronze skin, the measured wake-drag coefficients were rather constant. The values of drag measured in the center region are believed to correspond to true two-dimensional conditions and are essentially uninfluenced by the flow disturbances outside this region.

The drag coefficients measured at a station 1 inch to the right of the model center line are representative of the fairly constant value over the center 3 to 4 inches and are plotted against suction-flow coefficient in figure 2(a) for Reynolds numbers from 5.9×10^6 to 19.8×10^6. The variation of drag coefficient with suction-flow coefficient C_Q is similar for all Reynolds numbers investigated; that is, an abrupt decrease in drag to a value of about 0.0008 occurs at some critical value of C_Q dependent upon the Reynolds number and is followed by a much more gradual decrease with an increase in C_Q. Full-chord laminar flow is indicated for all values of wake-drag coefficient of about 0.0008 or less, inasmuch as boundary-layer profiles measured during the initial part of this investigation, as reported in reference 1, indicated that the boundary layer changed rapidly from turbulent over a large portion of the airfoil to laminar over virtually the full chord whenever a large decrease in drag accompanied a small increase in flow coefficient. The gradual reduction in drag with a further increase in C_Q above the value at which the large drag change occurs corresponds only to a progressive thinning of the full-chord laminar boundary layer. For the tests of reference 1, the sudden forward movement in point of

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transition from laminar to turbulent flow with a small decrease in C_Q was caused by outflow of air through the surface when the static pressure inside the skin was greater than the minimum static pressure on the outside of the airfoil. For the present tests, the skin was dense enough so that no outflow of air occurred for all values of C_Q and Reynolds number investigated. The cause of the rapid increase in drag and corresponding forward movement of transition observed in the present tests is revealed by a comparison of the values of C_Q at which the rapid drag rises occurred (fig. 2(a)) with the minimum theoretical values of C_Q required to keep the laminar boundary layer stable. The theoretical values of C_Q required to keep the laminar boundary layer stable with a constant chordwise inflow on the NACA 64A010 airfoil are presented in the following table and were obtained from reference 1:

R	Theoretical C_Q for constant inflow
5.9×10^6	0.00096
12.0	.00067
15.0	.00060
19.8	.00054

The comparison shows very close agreement between the experimental and theoretical values of C_Q required for full-chord laminar flow and indicates that the rapid drag rise was caused by insufficient suction to stabilize the laminar layer.

The maximum Reynolds number at which recorded data were obtained was 19.8×10^6. During the tests, however, at a value of C_Q less than 0.001, full-chord laminar flow was maintained up to a Reynolds number of about 24×10^6 as evidenced by a visual observation of the drag manometer which indicated values of the drag coefficient of about 0.0006. Unfortunately, however, a sudden change in the model occurred before any data could be recorded. It was found that the bronze skin had buckled to such an extent that it was impossible to repeat the full-chord laminar-flow tests at Reynolds numbers somewhat lower than 20×10^6, although before the skin took the permanent set, repetition of the low-drag results could be made.

The laminar stability theory indicates that, at a given value of chord Reynolds number, it should be possible to maintain full-chord laminar flow if sufficient area suction is applied to prevent the actual boundary-layer Reynolds number from exceeding a critical

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value (reference 1). Inasmuch as full-chord laminar flow was obtained experimentally with suction-flow coefficients that agreed very well with the theoretical values, it appears that the theoretical concepts with regard to area suction are valid. It seems most likely, therefore, that Reynolds number itself is not a limiting parameter in attainment of full-chord laminar flow provided that the airfoil surfaces are kept sufficiently smooth and fair and provided that outflow of air through the surface is prevented. Quantitative information on the effects of surface roughness or fairness on the stability of the laminar boundary layer, however, are not yet available, although some indications of adverse effects of roughness on the ability to maintain full-chord laminar flow were indicated in reference 1.

Total drag.- An indication of the section total-drag coefficient, including the drag equivalent of the suction power required, is presented in figure 2(b). The suction-drag coefficient based on the model chord was calculated as the suction-flow coefficient C_Q times the suction-air pressure-loss coefficient C_P, which is the drag equivalent of the power required to pump the suction air back to free-stream total pressure. (See reference 1, appendix B.) In this method of calculating suction drag, the over-all pumping efficiency is considered to be equal to that of the main propulsive system.

The dashed curve of figure 2(b) represents the variation of c_{d_s} with C_Q for an assumed constant value of C_P equal to 1.30. This value of C_P was chosen in order to present an indication of the minimum suction-drag coefficient required to maintain full-chord laminar flow at any value of the suction-flow coefficient and Reynolds number. A value of C_P slightly lower than 1.30 would result in outflow of air through the surface and a forward movement in transition from laminar to turbulent flow, inasmuch as the minimum local pressure on the airfoil exterior corresponds to a value of pressure coefficient S equal to 1.29. For the porous bronze skin used in the present tests, a value of C_P equal to 1.32 was measured at a value of C_Q of about 0.0007 at a Reynolds number of 19.8×10^6. The curves of section total-drag coefficient plotted against C_Q (fig. 2(b)) are the sums of the suction and wake drags. The minimum section total-drag coefficient decreased with an increase in Reynolds number because of the decrease in C_Q required to obtain low wake drags. At a Reynolds number of 19.8×10^6 the minimum c_{d_T} was 0.0017 as compared with a value of about 0.0045 (estimated from data of reference 4) for an NACA 64A010 airfoil without boundary-layer control at a Reynolds number of 20×10^6.

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CONCLUDING REMARKS

Results were presented of a two-dimensional wind-tunnel investigation of an NACA 64A010 airfoil with a porous surface of sintered bronze. Full-chord laminar flow was maintained by the application of area suction up to a Reynolds number of 19.8×10^6. At a Reynolds number of 19.8×10^6, the total-drag coefficient (wake drag plus the drag equivalent of the suction power required) was equal to 0.0017 as compared with an estimated value of 0.0045 for a smooth and fair NACA 64A010 airfoil without boundary-layer control at a Reynolds number of 20×10^6. Excellent agreement between experimental and theoretical suction quantities required for full-chord laminar flow was obtained through the complete range of Reynolds number investigated. It seems likely from the results that attainment of full-chord laminar flow by means of continuous suction through a porous surface will not be precluded by a further increase in Reynolds number provided that the airfoil surfaces are maintained sufficiently smooth and fair and provided that outflow of air through the surface is prevented.

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National Advisory Committee for Aeronautics
Langley Air Force Base, Va., April 12, 1950

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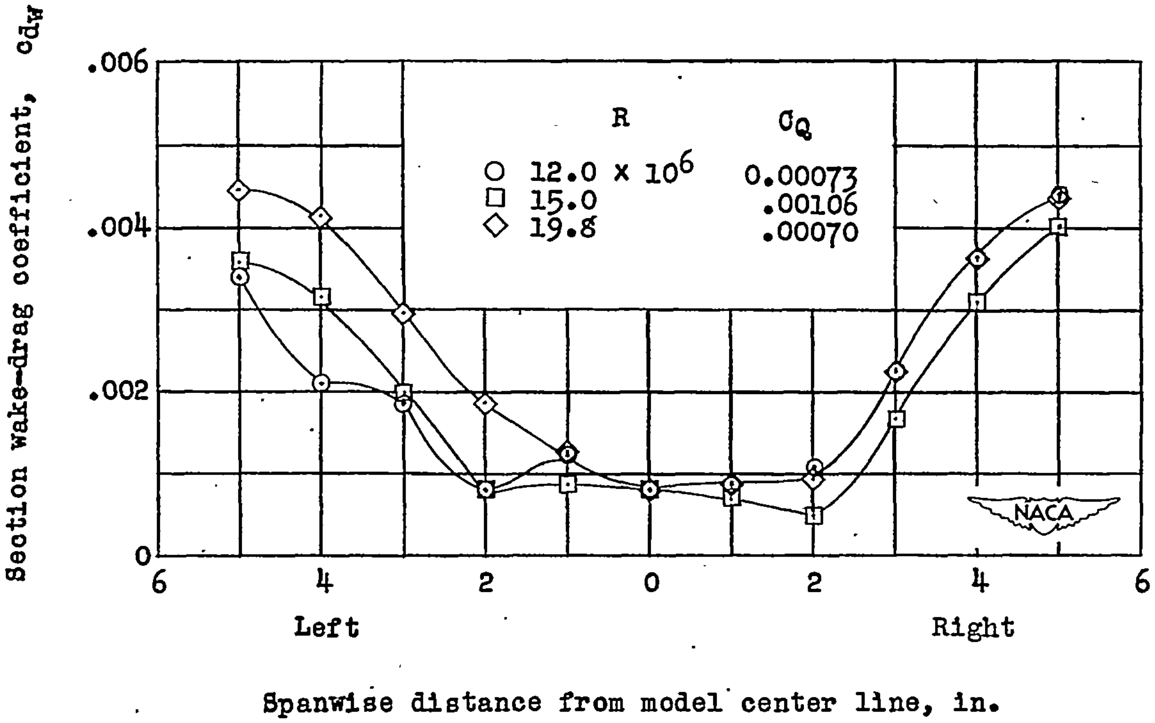

Figure 1.- Spanwise variation of section wake-drag coefficient on porous bronze NACA 64A010 airfoil model for three Reynolds numbers and suction-flow coefficients; $\alpha_o = 0^\circ$.

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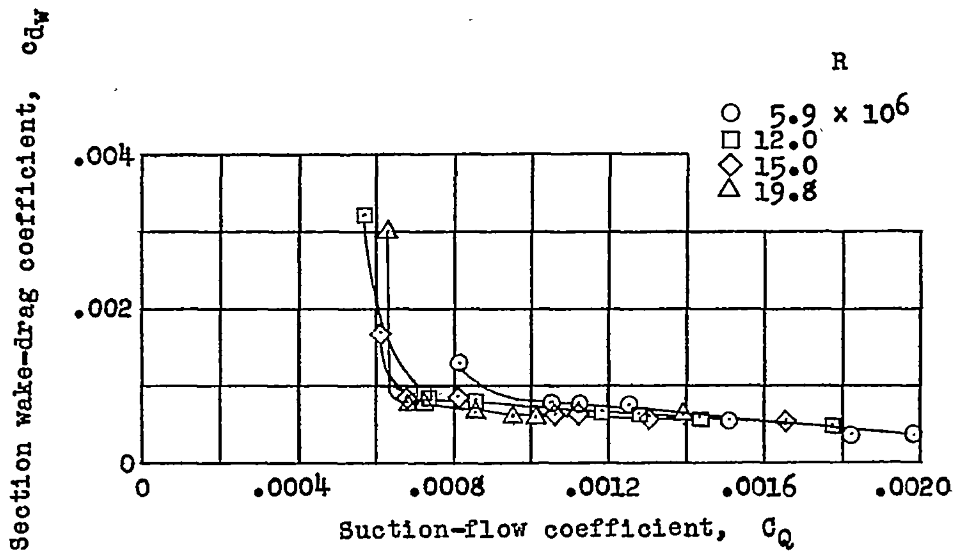
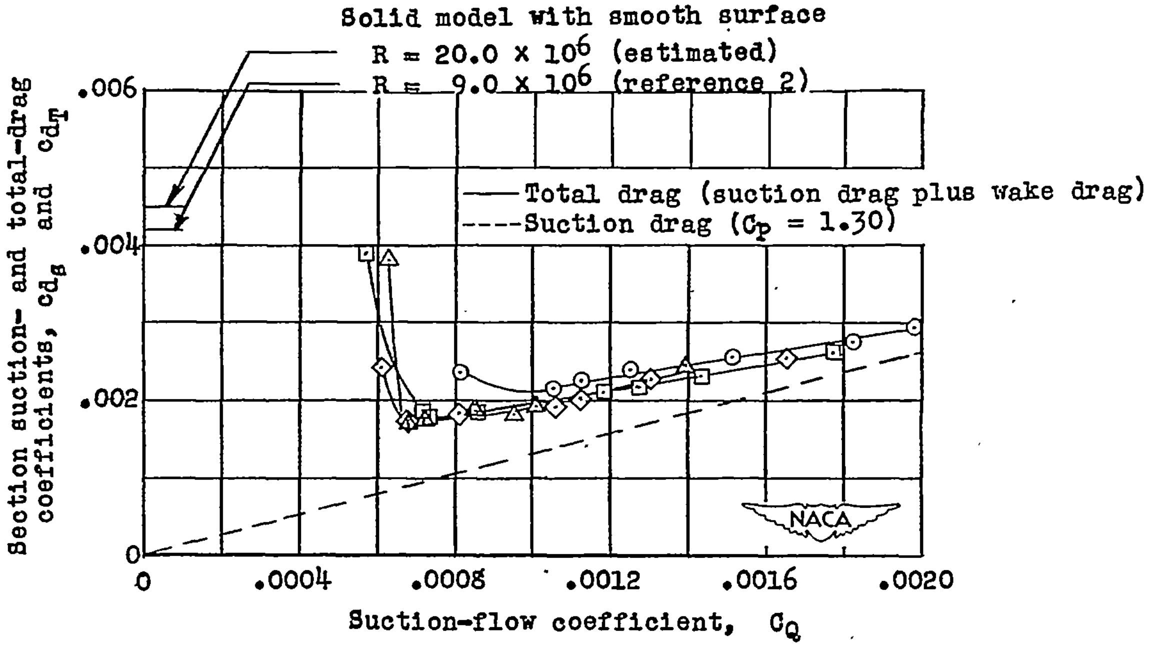


(a) Wake drag.



(b) Total and suction drag.

Figure 2.- Variation of section drag coefficients with suction-flow coefficient for porous bronze NACA 64A010 airfoil model; $\alpha_0 = 0^\circ$.

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