TECHNICAL NOTES

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FLOW OBSERVATIONS WITH TUFTS AND LAMPBLACK OF THE STALLING OF FOUR TYPICAL AIRFOIL SECTIONS IN THE N.A.C.A. VARIABLE-DENSITY TUNNEL

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SUMMARY

A preliminary investigation of the stalling processes of four typical airfoil sections was made over the critical range of the Reynolds Number. Motion pictures were taken of the movements of small silk tufts on the airfoil surface as the angle of attack increased through a range of angles including the stall. The boundary-layer flow also at certain angles of attack was indicated by the patterns formed by a suspension of lampblack in oil brushed onto the airfoil surface. These observations were analyzed together with corresponding force-test measurements to derive a picture of the stalling processes of airfoils.

INTRODUCTION

The stalling characteristics of an airfoil section are among its most important aerodynamic properties, not only because the value of the maximum lift coefficient determines the wing loading permissible for a given stalling speed but also because these characteristics influence the manner of stall of tapered wings, which is intimately connected with lateral stability and damping in roll at the stall. A discussion of the mechanism of the stall is given in reference 1, in which the stall is considered to be caused by laminar or turbulent separation resulting in general flow breakdown; the type of separation is governed by the airfoil section and the Reynolds Number and is influenced by the general boundary-layer conditions. Although much experimental and theoretical study has been devoted to the mechanism of the stall, the phenomena which occur are so complex that the understanding of the subject remains unsatisfactory.

The present preliminary investigation was undertaken to study the stalling of four typical airfoil sections over the critical range of the Reynolds Number in the N.A.C.A. variable-density tunnel. This investigation is to be extended to include the stalling of tapered wings in the N.A.C.A. variable-density tunnel and of airfoil sections in flight and in wind tunnels of much less turbulence than that of the N.A.C.A. variable-density tunnel. It is expected that the results of these investigations, together with advances in boundary-layer theory, will provide some additional information leading to a better understanding of the nature of the stall and of the effects of wind-tunnel turbulence on airfoil data.

Motion pictures of the movements of small silk tufts on the airfoil surface were made as the airfoil passed through the stall. As an indication of the boundary-layer flow, patterns formed by a suspension of lampblack in oil brushed onto the airfoil surface were observed at certain angles of attack. These observations were correlated with force-test measurements to provide a partial picture of the stalling processes of the airfoil sections under the flow conditions of the variable-density wind tunnel.

METHOD

The models employed were the N.A.C.A. 0009 and 8318 rectangular, square-tip airfoils and the N.A.C.A. 0012 and 4412 rectangular, rounded-tip airfoils. The tests were similar to the usual force tests (reference 2) except that two angle-of-attack stings instead of the usual single sting were used to eliminate interference at the midsection of the airfoil. The only force measurements made were readings of the lift coefficients near the stall.

For the observations of the general flow above the airfoil surface, fine silk tufts were employed; their length and spacing were of the order of 1/4 inch. They were affixed by their front ends to the airfoil upper surface near the midsection and their positions were staggered to minimize mutual interference. A remotely operated 16-millimeter motion-picture camera was used to take the picture records, the tunnel lights being dimmed momentarily at specified values of the continuously increasing angle of attack to indicate the angle of attack on each film.

For the boundary-layer patterns, lampblack was suspended in oil of various viscosities, the viscosity being changed to suit the tunnel operating conditions, and was brushed onto the airfoil in as thin a film as possible. The observations were made at fixed angles of attack to obtain patterns of the flow for steady conditions. Motion-picture records, supplemented by visual observations when possible, were obtained of the formation of the patterns. Position measurements of the prominent lines and regions in the lampblack patterns were obtained after each run. Although some features of most of the patterns changed slowly with time after the air flow was stopped because the oil ran over the surface, it is believed that these measurements represent the pattern with a fair degree of accuracy.

The tufts were expected to describe the general flow over the airfoil, and the lampblack in oil was expected to indicate the nature of the flow in the boundary layer. It is important to recognize the possibility that the tufts or the lampblack may have changed the character of the flow by their presence. This effect, however, is believed to have been small, inasmuch as the values of the maximum lift coefficients agreed with the values previously obtained without tufts.

RESULTS AND DISCUSSION

Figures 1 to 4 present the results of the tuft observations correlated with the corresponding section lift curves derived from force-test data. The flow representations are grouped in columns corresponding to the different values of the effective Reynolds Number R_e; the ordinate position of each representation corresponds to the section angle of attack α_0. Important features of the flow in the boundary layer as deduced from the lampblack patterns are indicated on the figures by appropriate symbols. Where symbols are lacking, no measurements were made.

Interpretation of data.- In the interpretation of the tuft observations, the two conditions termed "unseparated" and "fully separated" flow were easily distinguishable. For unseparated flow, the tufts would ordinarily lie flat on the airfoil surface without movement; for separated flow, the tufts fluctuated violently in direction, sometimes disappearing entirely from the pictures but generally indicating a strong reversed flow. The details of the transition from unseparated to fully separated flow varied with the different airfoils and with the values of the Reynolds Number.

In some cases, such as for the N.A.C.A. 4412 airfoil, the first fluctuations of the tufts as the angle of attack of the airfoil was increased were small uncertain movements of those nearest the trailing edge. Such movements were considered to be caused by the relatively thick turbulent boundary layer, and the flow is considered to be unseparated.

In other cases, the first movements of the tufts were sudden, violent flicks in which the flow indicated by the tufts completely changed direction. These flicks might occur over either a small or a large region. Sometimes these flicks were of very short duration, occurring only for the length of time required for the air to travel two or three chord lengths. As the angle of attack increased, these flicks commonly became more frequent and of longer duration. The flow in this case is represented in figures 1 to 4 as "momentarily separated."

As the flicks became more frequent and of longer duration, a point was reached where the time during which the flow was separated was of the same order as the time of unseparated flow. Such a condition is defined as being "intermittently separated." This condition often occurred without the intervention of the sudden short flicks previously mentioned.

In the case of the lampblack-in-oil observations, study of motion-picture records and visual observation indicated that the first movements of the very thin film usually consisted of a downstream flow from the leading edge and a cleaning out of the film by both upstream and downstream movements from some point downstream from the location of the peak negative pressure. In the intermediate region, two sharp lines of lampblack and oil developed. These lines might either be merged or be separated by an appreciable distance, in which case the film between them remained undisturbed by the flow. In all cases, the distance between the first sharp line and the downstream point from which the film moved in both directions decreased at increased Reynolds Numbers or reduced angles of attack, the entire pattern disappearing at sufficiently low angles. The distance between the two sharp lines varied accordingly. The general appearance of a pattern is shown in figure 5. The sketch (fig. 5a) points out the most definite features usually observed in a lampblack pattern as they occurred on the N.A.C.A. 8318 airfoil. (See fig. 5b.) Before the photograph (fig. 5b) was taken, incidentally, the pattern had run appreciably, losing its original sharpness.

The proper interpretation of such patterns is doubtful, but the variations of the pattern with angle of attack and Reynolds Number correspond closely to what would be expected from consideration of the boundary-layer conditions on the basis of the following tentative interpretation.

The first, or upstream, sharp line is thought to be associated with a local reduction in the shearing forces at the surface of the airfoil. Such a reduction in the shearing forces may be caused by laminar separation and, for brevity, the location of this line will be referred to as "point of laminar separation." The point from which the film moved in both the upstream and the downstream directions is considered to be the point where the flow returns to the surface as the result of the formation of turbulence. The second sharp line then becomes the upstream limit of the region of strong reversed flow under the overrunning boundary layer.

On the basis of this interpretation, the patterns show the increased difficulty experienced by the flow in returning to the surface after laminar separation at high angles of attack or at low values of the Reynolds Number. Eventually this process, in the case of the N.A.C.A. 0009 and 0012 airfoils, leads to complete flow separation from near the leading edge, as indicated by the tuft observations. In the case of the N.A.C.A. 4412 and 8318 airfoils, the stall occurs by progressive separation from near the trailing edge before the laminar separation becomes sufficiently severe to cause complete flow breakdown.

The positions of the first sharp line of the patterns are tabulated in table I together with some theoretical separation points computed for the same conditions by the method of reference 3. The most important features of the boundary-layer flow, as indicated by the foregoing interpretation, are shown in figures 1 to 4. Some features have been omitted from the presentation because of difficulty in measuring or interpreting the patterns. In particular, the point where the flow is considered to return to the surface is often omitted because too little lampblack remained in this region to permit measurement after the pattern was formed. On account of these difficulties and the possibility that the accumulation of the lampblack may affect the flow, the use of this method for the study of the boundary layer is not advocated.

N.A.C.A. 0009 airfoil.- The results for the N.A.C.A. 0009 airfoil are presented in figure 1. This airfoil is an example of the type in which the stall is influenced primarily by the laminar separation occurring near the leading edge. In the lower critical range of the Reynolds Number, the first evidence shown by the tufts of the approaching stall is momentary separation occurring at the leading edge followed by intermittent separation either spreading downstream from the leading edge or occurring simultaneously over the whole upper surface. The completely separated region grows backward to cover the entire upper surface. If the lift is sufficiently low, however, it continues to increase to about the maximum lift coefficient for a flat plate.

At a value of the effective Reynolds Number of 3,400,000, the action is similar to that in the lower range except that momentary separation first occurs near the trailing edge, which probably indicates separation of the turbulent boundary layer. The separated region does not grow forward but probably influences the momentary separation that suddenly occurs over the entire upper surface; the stall then develops much the same as at the lower values of the Reynolds Number. At the higher values of the Reynolds Number, intermittent separation occurs simultaneously over the entire upper surface.

N.A.C.A. 0012 airfoil.- At the lower end of the critical Reynolds Number range, the stalling process for the N.A.C.A. 0012 airfoil (fig. 2) is similar to that for the N.A.C.A. 0009 airfoil, in that separation grows back from the leading edge to cover the entire upper surface and then increases in intensity with increasing angle of attack. At the higher Reynolds Numbers in the critical range, the separation starts at the trailing edge and probably influences the complete flow breakdown from the leading edge that occurs at larger angles of attack.

N.A.C.A. 4412 airfoil.- The characteristics of the stalling process for the N.A.C.A. 4412 airfoil (fig. 3) appear to be opposite to those for the N.A.C.A. 0009 airfoil. Separation grows forward from the trailing edge with increasing angle of attack, evidently as a result of progressive separation of the turbulent boundary layer. Separation originates at lower angles of attack as the Reynolds Number is increased and the stalling process covers a larger range of angles, the maximum lift coefficient being higher at the higher values of the Reynolds Number. There are no sudden changes in the character of the flow in the region of the stall. The overrunning flow appears to be unaffected by the laminar separation indicated by the lampblack tests, but the presence of this laminar separation probably influences the turbulent separation near the trailing edge. (Compare reference 1.)

N.A.C.A. 8318 airfoil.- Figure 4 shows the stalling processes for the N.A.C.A. 8318 airfoil, which are somewhat similar to those for the N.A.C.A. 4412. At a value of the effective Reynolds Number of 200,000, a sudden sharp drop in lift occurs at the maximum and is accompanied by a corresponding sudden change in the character of the flow. At all values of the effective Reynolds Number for which tests were made, except for a value of 800,000, the tufts showed separation phenomena at the middle of the section corresponding roughly with the region of reversed flow indicated by the lampblack at the lower values of the Reynolds Number. In general, however, the stall results from progressive separation of the turbulent boundary layer, the separated region growing forward from the trailing edge. The leading edge resists the process of separation much more markedly than does that of the N.A.C.A. 4412.

General stalling processes.- The stalling processes shown by these tests are in agreement with the discussion of stalling presented in reference 1. The final flow breakdown occurs either as leading-edge separation, caused by separation of the laminar boundary layer and failure to reestablish the flow through the formation of turbulence, or as separation of the turbulent boundary layer near the trailing edge. These two stalling processes are not, however, separate phenomena occurring independently but are intimately related, the actual point of separation and its growth being influenced by the general boundary-layer conditions.

When separation occurs near the leading edge (figs. 1 and 2), it usually causes a sudden drop in lift either with or without violent fluctuations between the two conditions of stalled and unstalled flow. In the case of the N.A.C.A. 0009 airfoil (fig. 1), this type of separation occurred at all values of the Reynolds Number; but, at the lower values, the flow was partly reestablished over a large portion of the chord and the stall was progressive. The reestablishment of the flow was facilitated by the low lift coefficient at the stall, which indicates relatively low adverse pressure gradients.

When separation occurred near the trailing edge (figs. 3 and 4), it progressed forward without any sudden flow changes or drops in the lift except in the case of the N.A.C.A. 8318 airfoil at the lowest value of the Reynolds Number tested, for which the final flow breakdown apparently occurred as the result of forward separation.

The question arises as to the extent to which the general flow is separated and to which the lift is affected when separation is shown by the tufts on the surface, particularly when the separation shown by the tufts is of short duration. In the present tests, the tufts often failed to show the local separation indicated by the lampblack, which indicated that the region of reversed flow was very shallow and had little effect on the general flow. Similarly, less shallow regions of reversed flow might be indicated by the surface tufts but have little effect on the lift coefficient. Jones (reference 4) studied the flow by means of tufts attached to small rods extending some distance from the airfoil surface, but little has been done to correlate the results of such studies with the effects on instantaneous lift for particular airfoil sections. Further study of the detailed flow changes and the accompanying fluctuations of the forces at the stall appears to offer a promising field of research leading to a better understanding of the effects of scale and turbulence as well as of the effect of the type of stall on airplane performance.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 7, 1938.

REFERENCES

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3. Von Kármán, Th., and Millikan, C. B.: On the Theory of Laminar Boundary Layers Involving Separation. T.R. No. 504, N.A.C.A., 1934.

4. Jones, B. Melvill: Stalling. R.A.S. Jour., vol. XXXVIII, no. 285, Sept. 1934, pp. 753-769.

TABLE I

Theoretical and Measured Laminar Separation Points

(Measured points obtained from lampblack patterns)

N.A.C.A. airfoil	R_e (millions)	α_0 (deg.)	c_l	Laminar separation points (percent of chord from leading edge)	
				Theoretical	Measured
0009	0.4	6.2	-	-	0.5
	6.1	11.0	1.080	0.3	.3
	8.2	11.0	1.080	.3	?
0012	.4	6.3	-	-	3.2
	.4	9.6	-	-	1.0
	.4	11.6	-	-	.5
	1.7	9.4	.910	1.6	1.3
	1.7	11.1	1.050	1.2	1.0
	1.7	11.9	1.100	1.2	.5
	3.4	9.4	.910	1.6	1.4
	3.4	14.2	1.339	.8	.4
4412	.4	10.3	-	-	1.6, 1.4
	1.7	10.2	-	-	1.2
	3.4	13.5	-	-	.9
8318	.2	8.3	-	-	21.5
	.4	8.0	1.420	22.6	21.6
	.8	8.0	1.445	22.1	26
	1.7	8.0	-	-	None

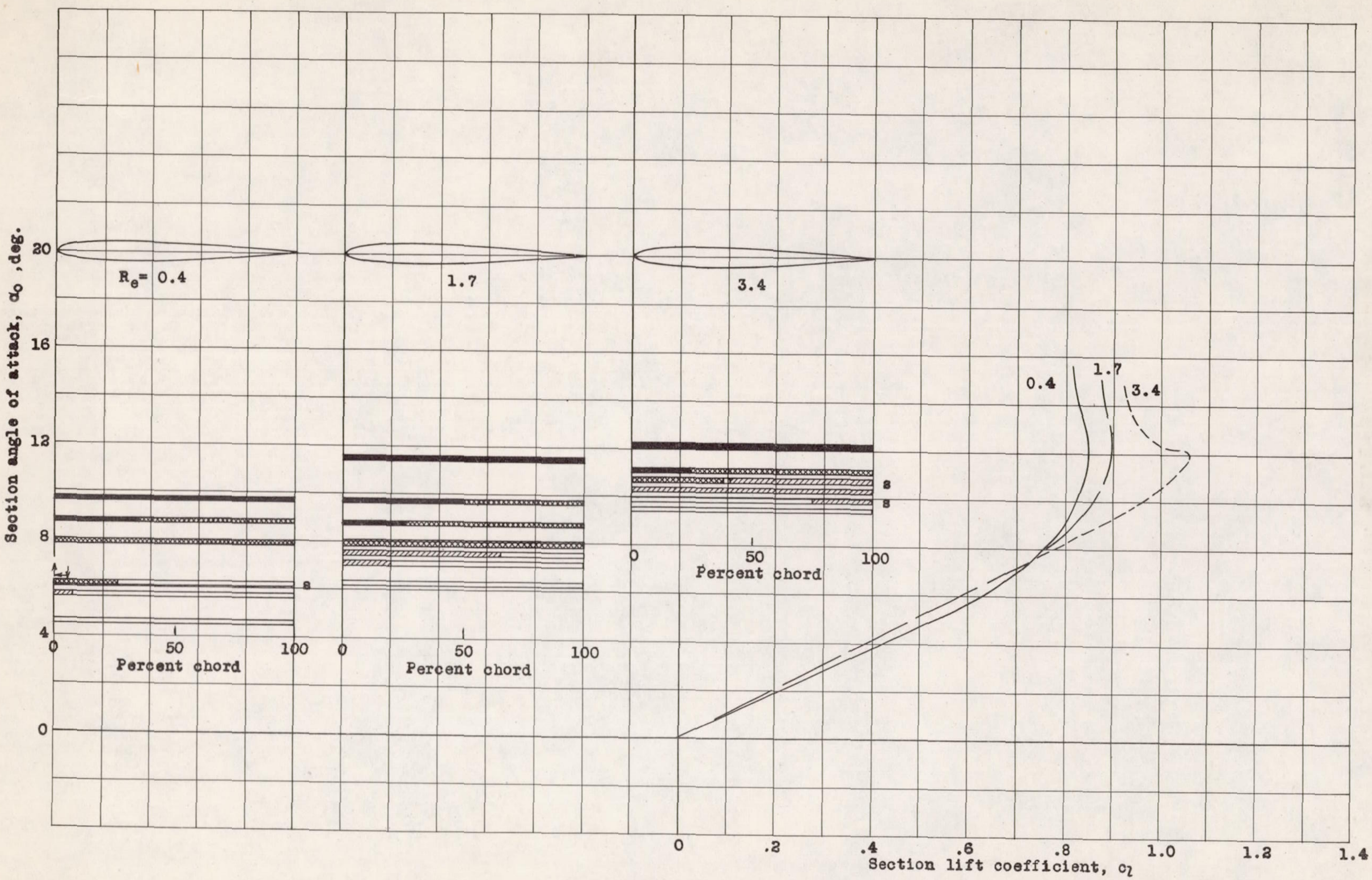

Figure 1a.- Flow observations on the N.A.C.A. 0009 airfoil. (See figure 1b for key)

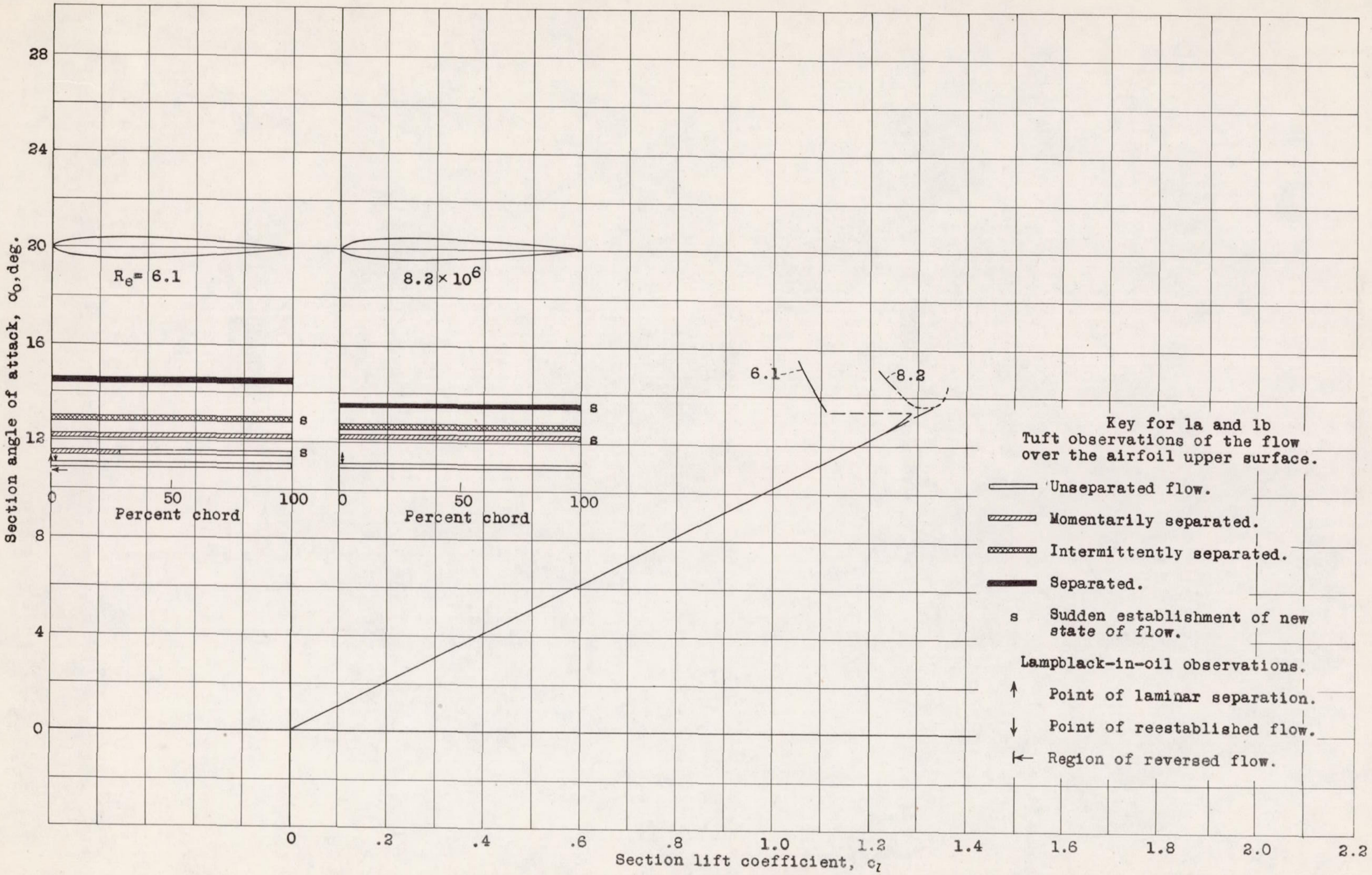

Figure 1b.- Flow observations on the N.A.C.A. 0009 airfoil.

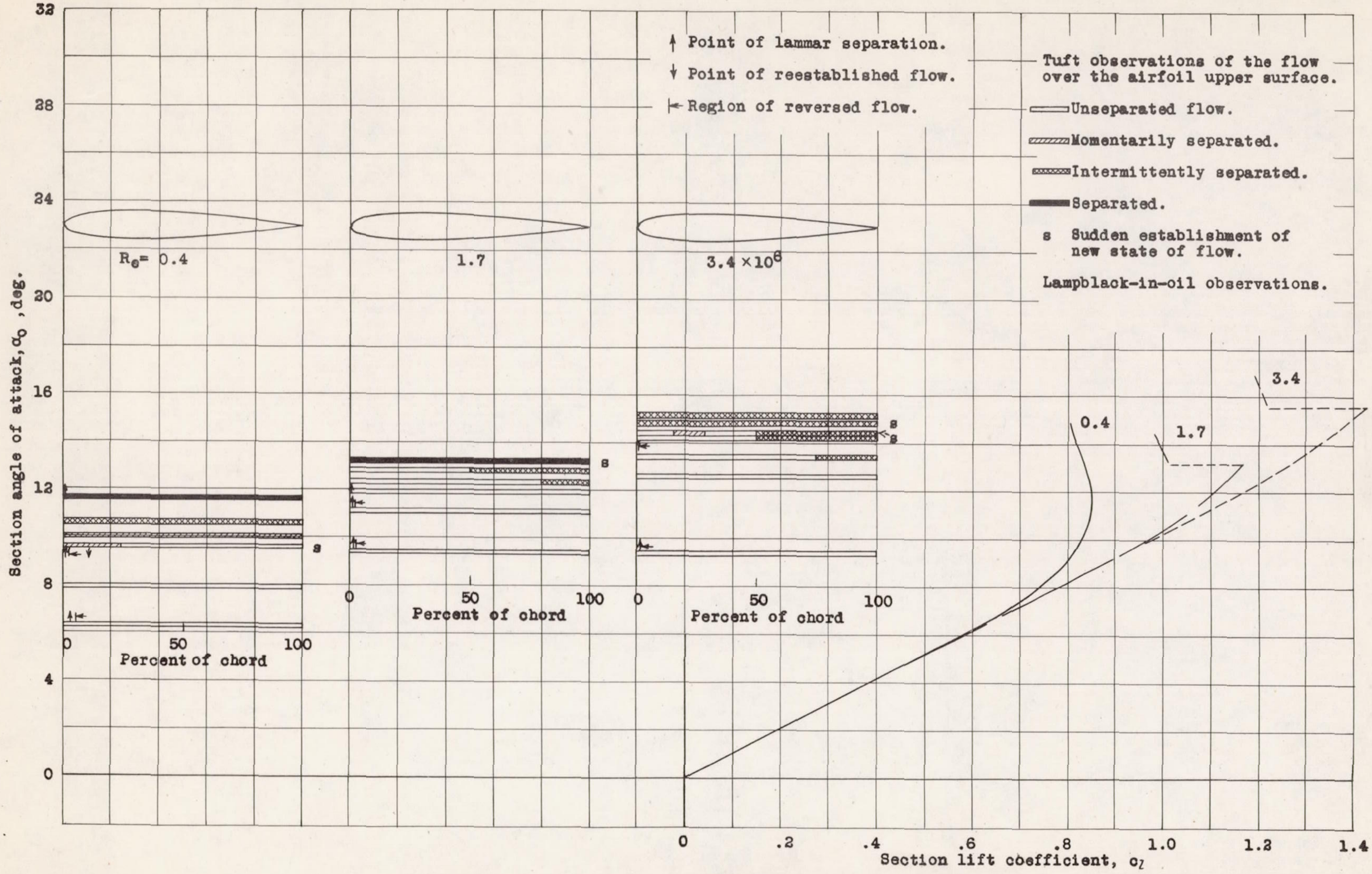

Figure 2.- Flow observations on the N.A.C.A. 0012 airfoil.

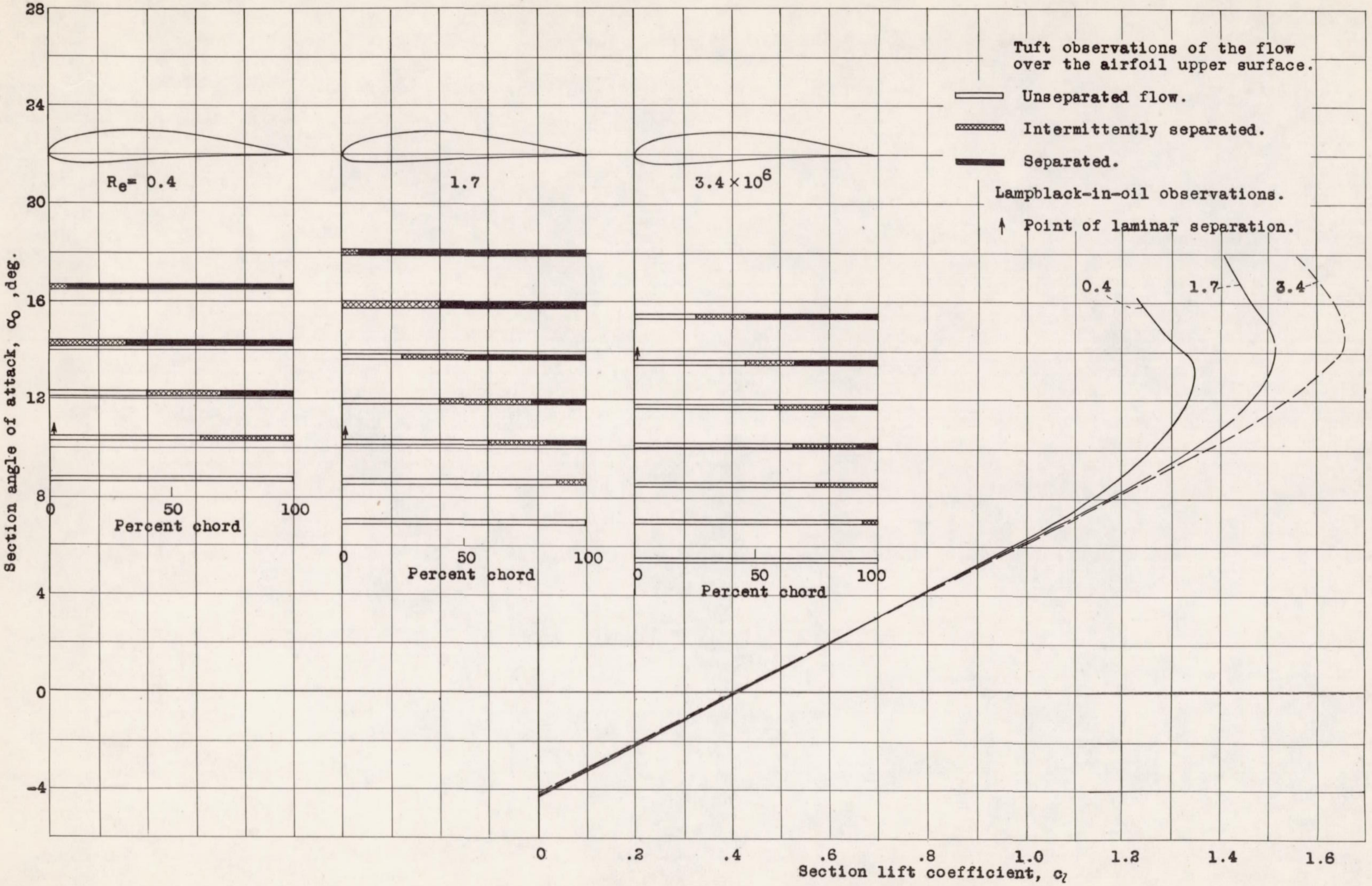

Figure 3.- Flow observations on the N.A.C.A. 4412 airfoil.

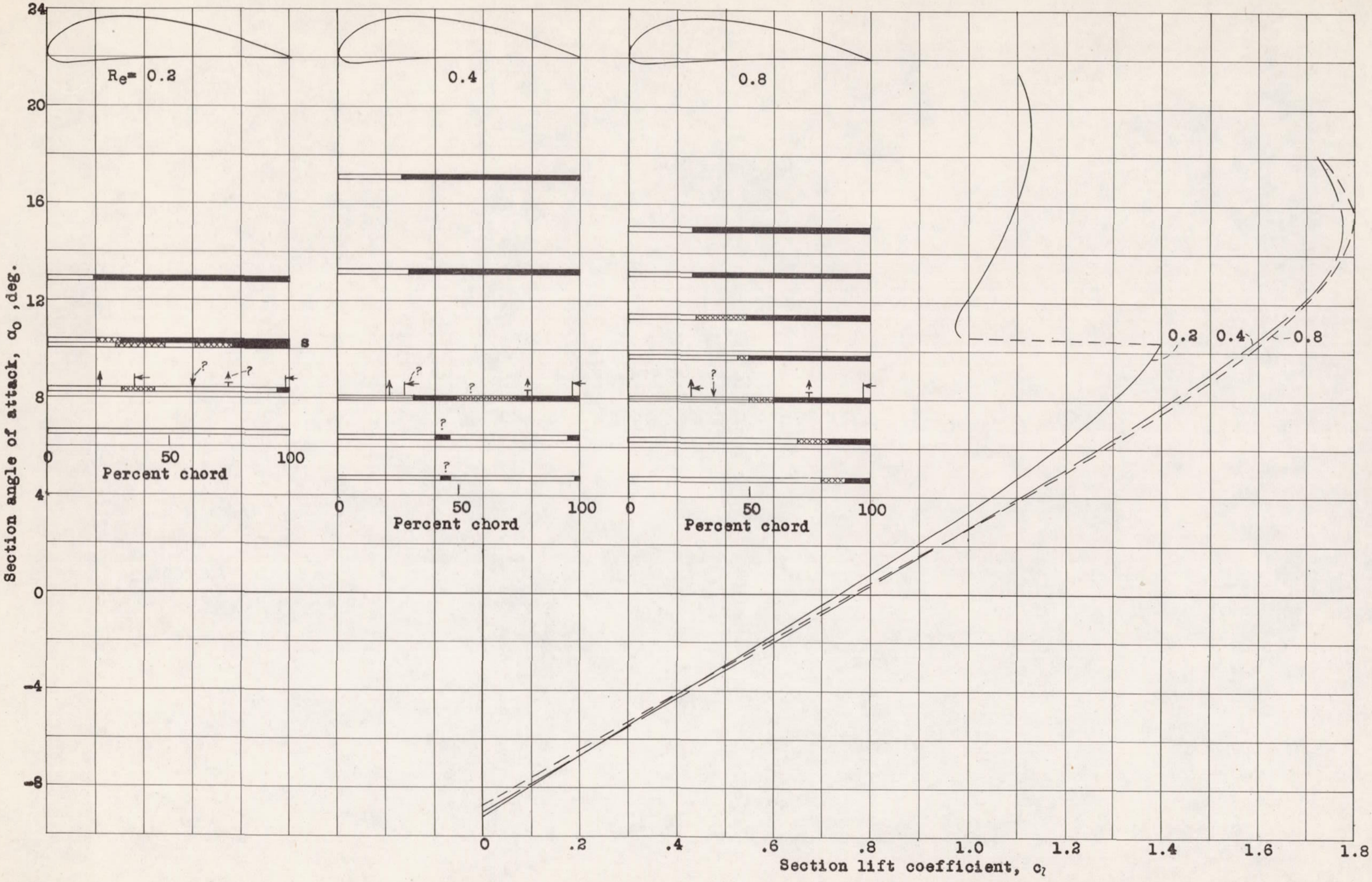

Figure 4a.- Flow observations on the N.A.C.A. 8318 airfoil. (See figure 4b for key)

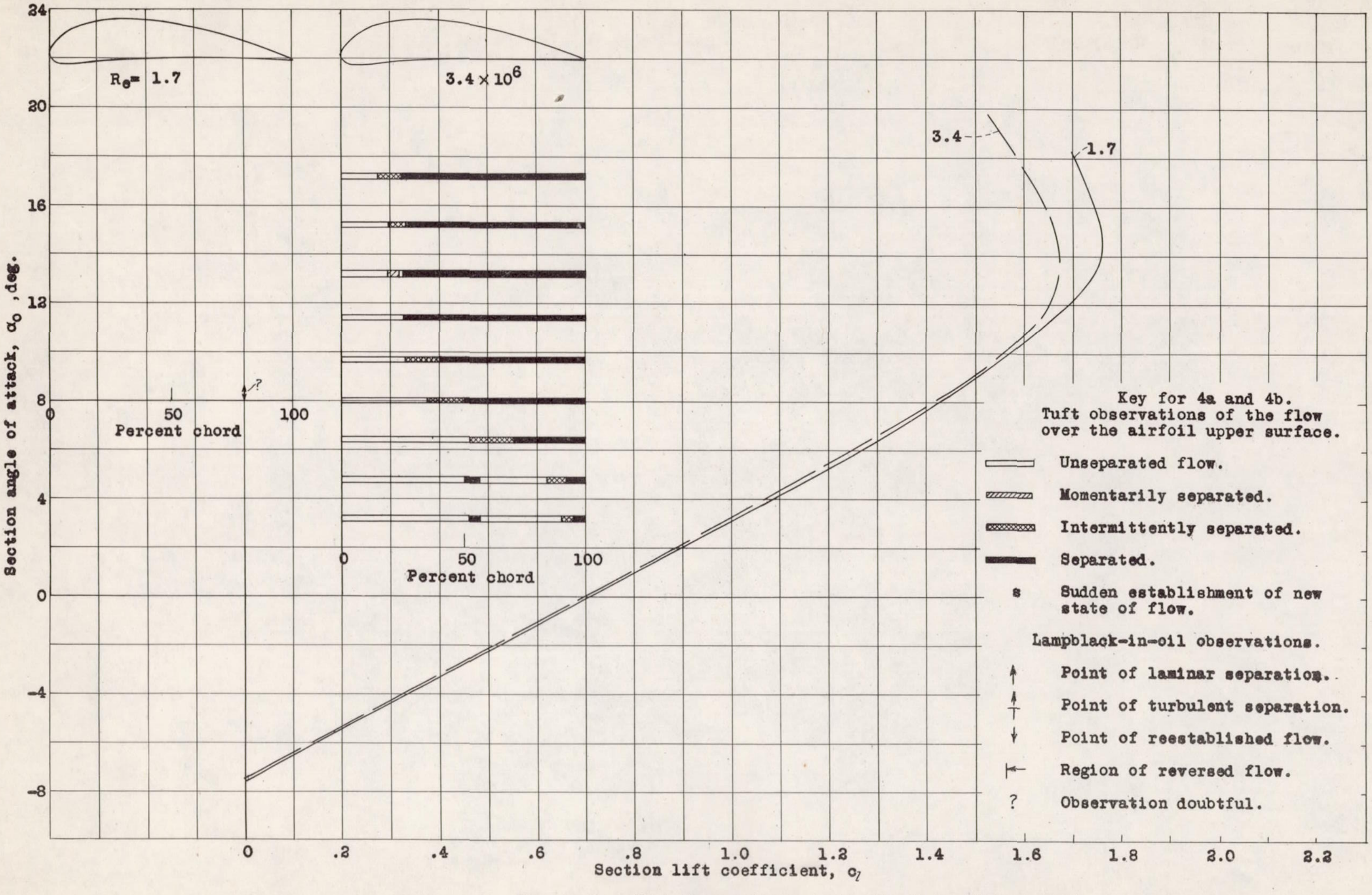

Figure 4b.- Flow observations on the N.A.C.A. 8318 airfoil.

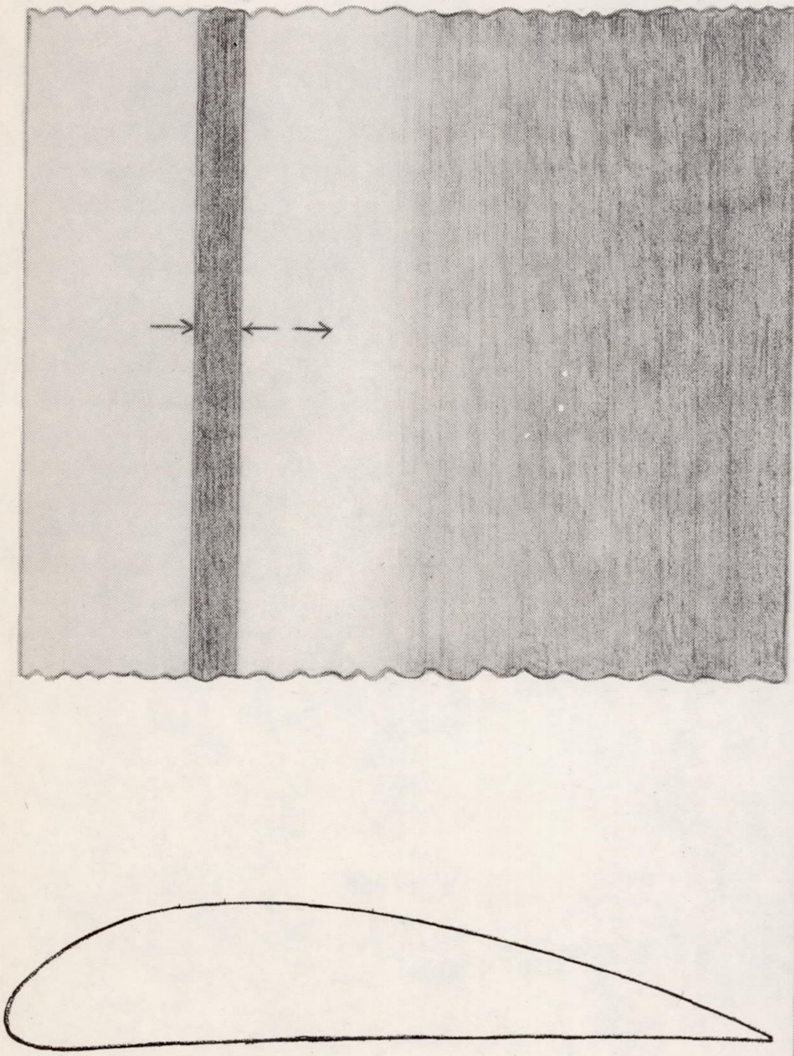

Figure 5a.- Sketch indicating general appearance of lampblack pattern on forward portion of N.A.C.A. 8318 airfoil. Arrows show direction of motion of lampblack.

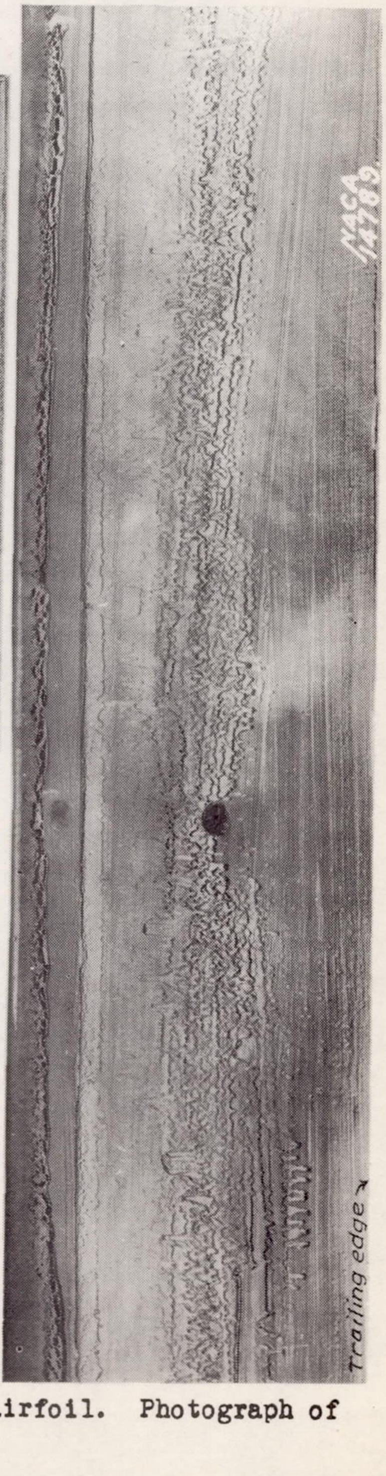

Figure 5b.- Lampblack pattern on N.A.C.A. 8318 airfoil. Photograph of pattern; α_o , 8.3° , R_e , 200,000.