Some Experiments with Cascades of Aerofoils

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Summary and conclusions.—Experiments were made to find an aerofoil section suitable for use in cascades at right-angle bends in a wind tunnel. A short length of duct, having a cross section of 12 in. × 15 in., was built into the high pressure end of the N.P.L. open jet tunnel No.2 for the experiments; wind speeds up to about 200 ft./sec. could be obtained in this duct. The chords of the various sections tested were all of the order of 2 in., so that a Reynolds number of about 2×10^5 could be reached. Measurements of the direction of flow behind the cascades were made with a yawmeter, while total head tubes were used to find relative pressure losses. The steadiness of flow was indicated by threads.

A section, described as section C, which caused only a very slight constriction of the air passing between the aerofoils, was found to be the most suitable of the sections tested. This section has a thin tail, the tangents to both surfaces at the tail being at right-angles to the incident stream. The experiments indicated that if it is desired to expand the duct section on passing through a cascade, an expansion ratio of about 1.15 should not be exceeded. Again, a polygonal shape is thought to be better than a smooth curve for the section of a duct at a cascade. It also appears that, if the vanes of a cascade are interlaced with thin strips at right-angles to their length, the cascade will also perform the functions of a honeycomb, without undue adverse effect on its efficiency as a cascade.

§1. *Introduction.*—The experiments to be described were undertaken with a view to the determination of a suitable design of aerofoil for use in cascades at the corners of a return flow wind tunnel. A wooden duct, of rectangular section, 15 in. high and 12 in. wide, was built into the high pressure end of the second N.P.L. open jet wind tunnel, the joint being suitably faired, so that a jet of air having a reasonably constant velocity across the section was obtained when the tunnel was running. The duct could be shut off at will by closing a door flush with the inside of the tunnel. Various cascades of vertical aerofoils were placed at the other end of the duct, and measurements were made with a yawmeter of the direction of flow behind these cascades. The distance of the yawmeter behind the cascades varied from about one to six chords. In addition, total head tubes were placed forward and aft of the cascades, and measurements were made of total head against atmospheric pressure. The static pressure in the stream aft of the cascade was very nearly atmospheric, so that the total head there was effectively equal to the dynamic head. A relative pressure loss figure (r) for each cascade was found by dividing the change in total head by the total head in the stream behind the cascade. The steadiness of flow and the presence of a breakaway of the flow from the aerofoils was examined by means of threads. The worth of a cascade was assessed in terms of the direction of flow behind it, the relative pressure loss, and the general steadiness of the flow.

Attention was restricted to the design of a cascade suitable for use in right-angle bends only. Moreover, most of the experiments related to a bend having an expansion ratio of unity; some experiments were, however, made with an expansion ratio of 1.2.

The majority of the experiments were carried out at a wind speed of about 50 ft./sec., corresponding to a value of Reynolds number R for the cascade aerofoils of about 5×10^4. A short investigation of scale effect was however made, the value of R rising to about 2×10^5.

§2. *The aerofoil sections.*—For the non-expanding corner, three shapes were used for the aerofoils; they will be designated as sections A, B and C. Section A (Fig. 1) was used in the cascades of the R.A.E. 5-ft. wind tunnel and in the N.P.L. open jet wind tunnels. This design involves a constriction of about 12 per cent. of the air as it passes between the aerofoils. Section B (Fig. 2) was designed from purely geometrical considerations to avoid a constriction. The concave surface is a 90° circular arc and the convex surface of the neighbouring aerofoil is also a 90° arc struck from the same centre but with an appropriately less radius: the remainder of this surface consists of two planes tangential to both arcs of the aerofoil. The leading and trailing edges are thus sharp, each having a common tangent lying in the direction of the stream. In practice the surfaces are slightly displaced to provide a finite thickness at the nose and tail (Fig. 3). Section C (Fig. 4) is obtained from Section B by rounding the leading edge in accordance with usual aerodynamical practice. The chords of sections A and B, measured in a straight line from nose to tail, were each about 2 in.; that of section C was therefore rather less. In all cases the spacing was 1 in.

For the experiments with an expansion ratio of 1.2, section B and two other sections, D and E (Fig. 5) were used. With section B, the expansion takes place as the air is turned between the aerofoils. Sections D and E were derived from section B by displacing the concave surface in a direction opposite to that of the incident stream, so that no expansion takes place while the air is being turned. The resulting aerofoil has a thick tail, and the expansion is obtained by fairing away this tail. Two different tails define the sections D and E.

§3. *Experiments at a non-expanding corner.*

(i) *The flow in the empty channel:* $V_T = 50$.—With a jet speed in the open jet tunnel of $V_T = 50$ ft./sec., the speed in the duct was about $V = 52$. Examination of the flow in a horizontal traverse $7\frac{1}{2}$ in. from the floor and ceiling showed that over the central region (6 in. wide) of the traverse the variation in yaw was only from $-0 \cdot 1°$ to $+0 \cdot 3°$, and the speed variation was from $V = 52 \cdot 7$ to $V = 52 \cdot 1$. Horizontal traverses at heights of 2 in. and 13 in. from the floor showed no remarkable differences, although there was evidence of a slight twist in the stream. There was a very slight drop in total head from the entry to the exit, giving a relative pressure loss of $r = 0 \cdot 00_5$. This has been applied as a correction to the relative pressure losses of all the cascades.

(ii) *A cascade of aerofoils of section A :* $V_T = 50$.—When a cascade of aerofoils of section A was placed at 45° to the direction of the incident flow and the stream behind the cascade was left free, the deflection ψ of the air over the central portion of the cascade varied from $82 \cdot 2°$ to $83 \cdot 0°$ at a speed of $V_T = 50$. The relative pressure loss r (averaged from a number of readings behind the cascade) was $0 \cdot 35_5$; and explorations with threads showed a considerable breakaway of the flow from the suction surface. The speed through the cascade varied from $V = 42 \cdot 9$ to $V = 44 \cdot 4$. When a short length of duct was added at 90° to the incident stream, so that the flow was to some extent constrained, the deflection varied from $86 \cdot 7°$ (nearer the outer wall) to $83 \cdot 4°$ over the same central portion ; the corresponding speeds were $V = 45 \cdot 2$ and $V = 43 \cdot 4$. The flow was definitely breaking away from the inner wall of the duct. As in the case of the empty duct there were no remarkable differences near the floor or ceiling ; and this was found to be the case throughout.

(iii) *Aerofoils of section B :* $V_T = 50$.—For this case, when the outflow was left free, the values of ψ ranged from $90 \cdot 4°$ to $91 \cdot 7°$ with a mean of $\psi = 91 \cdot 3°$, and those of V ranged from $47 \cdot 6$ to $49 \cdot 0$. The value of r was $0 \cdot 14$. The effect of constraining the flow by the short length of duct was only very slight. There was no appreciable breakaway from the walls of this duct. The flow was only slightly unsteady, in spite of the sharp noses of the aerofoils.

(iv) *Aerofoils of section C :* $V_T = 50$.—The mean deflection ψ for this case was $90 \cdot 3°$, with variations of about $\pm 0 \cdot 4°$. The mean speed was $V = 49 \cdot 2$. The flow was very steady, even on the suction side of the aerofoils ; and the relative pressure loss was only $r = 0 \cdot 11$.

(v) *Other experiments at* $V_T = 50$.—It was of interest to see whether a cascade of aerofoils could be made to perform also the functions of a honeycomb. The cascade of aerofoils of section C was therefore interlaced with horizontal steel strips, spaced 1 in. apart, and having a chord of about $1\frac{1}{2}$ in. The performance of this cascade was quite satisfactory. The mean deflection ψ was $89 \cdot 8°$ and the mean speed was $V = 47 \cdot 5$. The flow round the suction surfaces of the aerofoil was not so steady as in the case of the normal cascade, particularly in the immediate vicinity of the steel strips. The relative pressure loss was increased to $r = 0 \cdot 19$.

It was also felt to be of interest whether the performance of a cascade would suffer if it were used in a duct of section other than rectangular. The duct was therefore changed to an octagonal shape by the introduction of fillets in the corners. Tests in the empty duct showed a variation in yaw of $\pm$ 0·7° over the central section and a speed slightly slower than in the case of the empty rectangular duct. The performance of a cascade of aerofoils of section B was however unaltered, except that the flow was rather more unsteady, particularly near the fillets.

(vi) *Scale effect.*—The effect was examined of raising the value of V_T from 50 to 190 ft./sec. on the performance of cascades of aerofoils of sections A, B and C at 45° in the rectangular duct. For these measurements a multitube manometer was employed instead of Chattock gauges as in the experiments at $V_T = 50$. The measurements are thus rather less accurate than those hitherto given. In the following table, there is a possible error in ψ of about $\pm$ 0·3° and in V of about 0·7 per cent. The values of r have been corrected (see §3 (i)) by the subtraction of $0{\cdot}00_5$ and are thought to be accurate to this order.

V_T (approx.).		50	100	150	190
Reynolds No. (approx.)		5×10^4	9×10^4	14×10^4	18×10^4
Section A	ψ (deg.)	82·1	88·5	90·8	90·0
	r	$0{\cdot}36_5$	$0{\cdot}16_5$	0·12	0·11
Section B	ψ	91·1	89·9	89·0	88·7
	r	$0{\cdot}13_5$	0·11	0·10	0·09
Section C	ψ	90·4	89·0	88·7	88·6
	r	$0{\cdot}10_5$	0·07	0·06	0·05

It will be seen that the performance of section A improves greatly with speed. The deflection increases to approximately 90° and the relative pressure loss falls rapidly. Sections B and C both show a slight fall in deflection. The relative pressure loss of section C at the highest speed is however only about half those of sections A and B and is in fact only slightly in excess of the skin friction loss to be expected from the cascade surfaces.

§4. *Experiments at a corner with 20 per cent. expansion.*

(i) *Aerofoils of section B:* $V_T = 50$.—With an expansion ratio of 1.2, the width of the outflowing jet was about 14½ in. With a cascade of aerofoils of section B, the deflection over the central region (8 in. wide) of the middle traverse varied from 89·7° to 90·5°, with a mean value of 90·1°. The speed of outflow was about 46 ft./sec. There was a considerable breakaway from the suction surface compared with the non-expanding case (§3 (iii)), and the relative pressure loss was 0·19.

(ii) *Aerofoils of section D and section E:* $V_T = 50$.—Both of these sections caused a considerable overdeflection of the air at the corner. The mean deflection over the central area was 96·0° in the case of section D and 94·2° in the case of section E. There was no appreciable increase in steadiness. The wind speed was in both cases about 46 ft./sec., and the relative pressure loss was $0 \cdot 22_5$.

§5. *Conclusions.*—Of the five sections tested, section C gives the most consistent deflection of nearly 90° over the range of R used; moreover this section has much the best relative pressure loss. As regards expansion at a corner, the impression was gained that an expansion ratio of 1·2 was too large, in that there was rather too much breakaway from the suction surface, with a resulting increase in the unsteadiness of flow and in the relative pressure loss.

There would appear to be no great objection to the use of a duct section other than rectangular, although the latter is probably the best shape. A polygonal shape is probably better than a smooth curve, both from the point of view of the performance of the extreme aerofoils of the cascade and of difficulty of construction. Again, it appears that there is no objection to making a cascade perform also the duties of a honeycomb; in particular, if strength considerations were to require the aerofoils to be supported, this could be done by using a number of flat ties in planes perpendicular to the direction of the aerofoils.

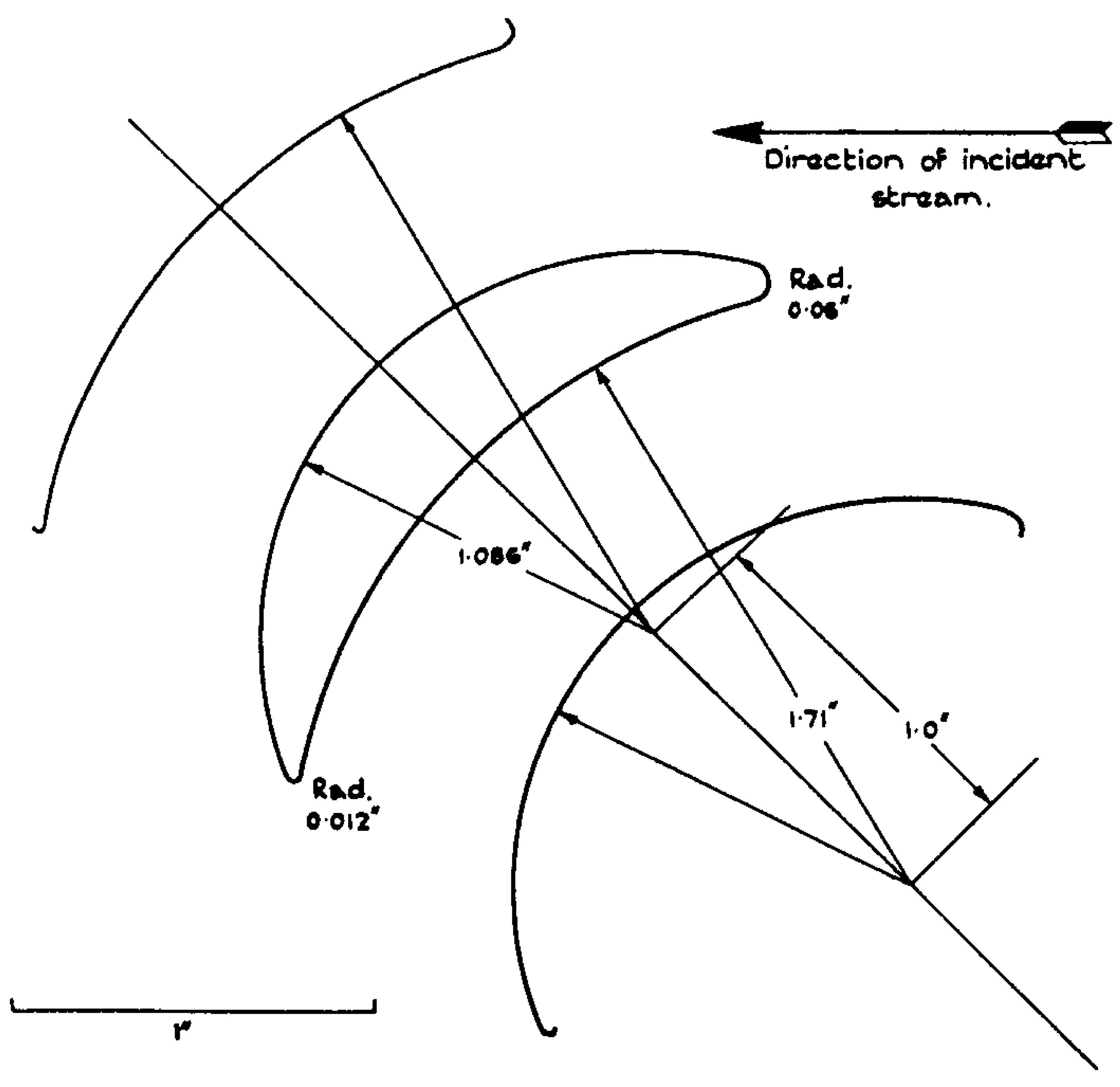

FIG. 1.—Section A.

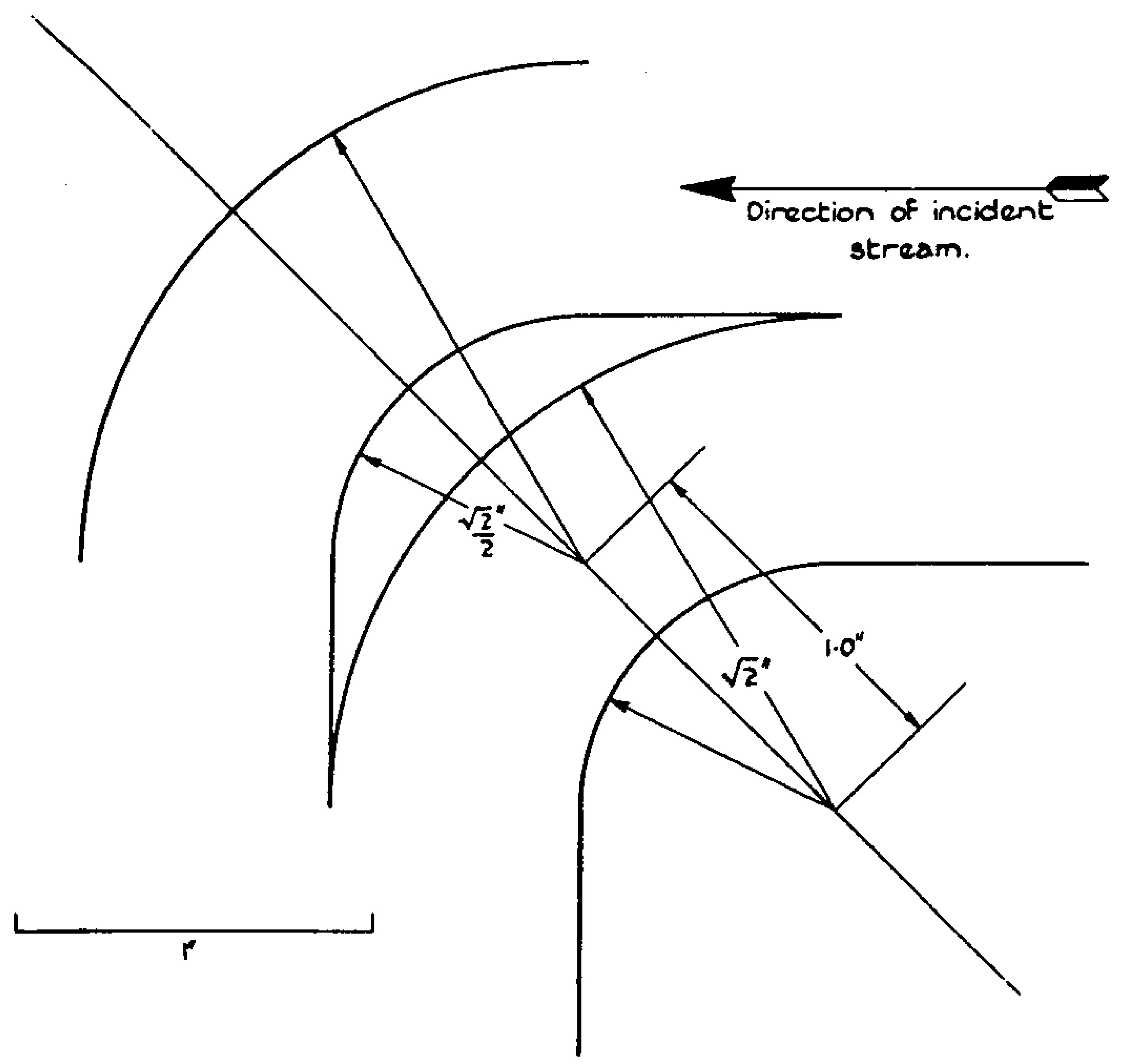

FIG. 2.—Section B. Geometrical Aerofoil.

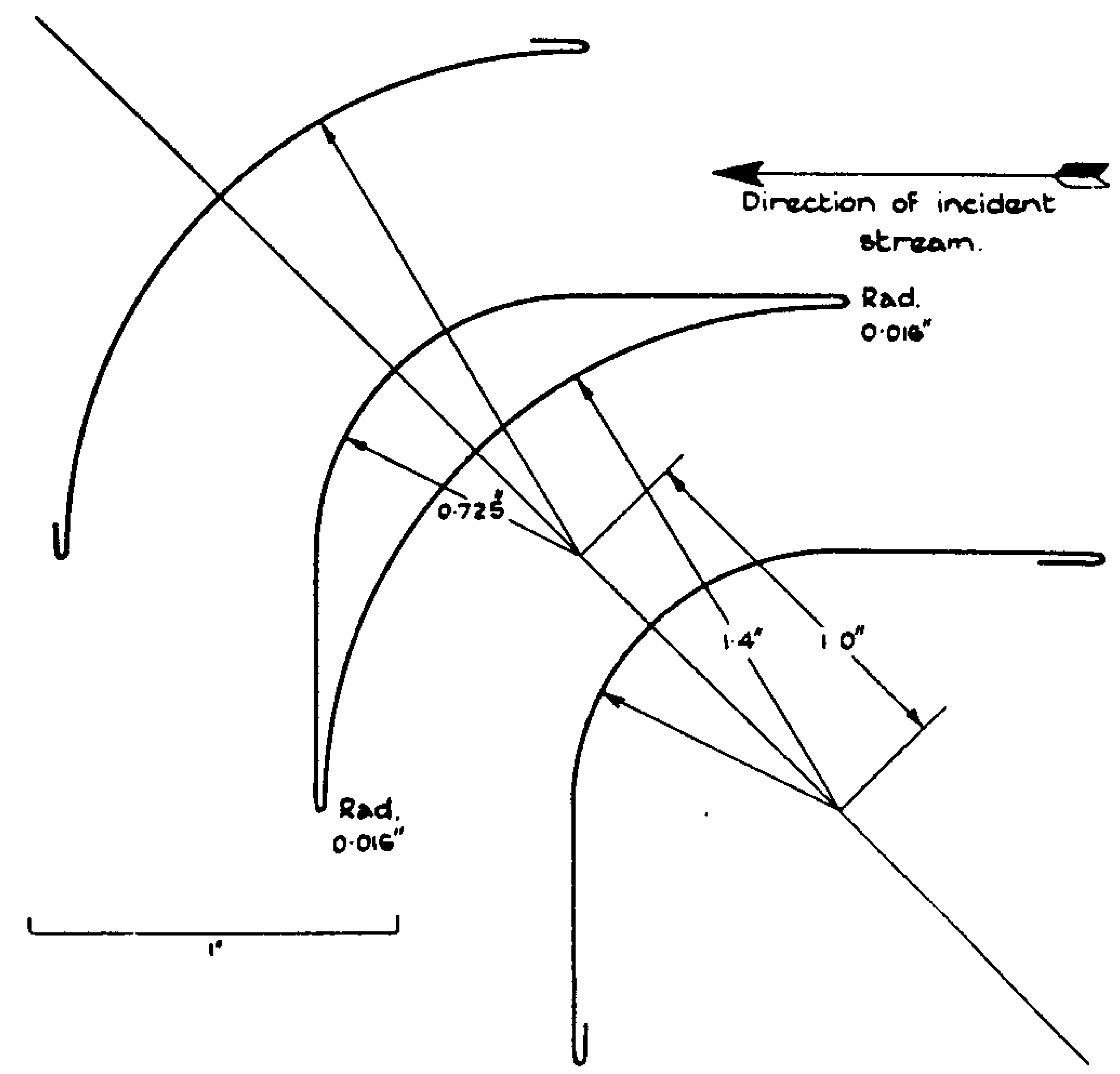

FIG. 3.—Section B. Practical Aerofoil.

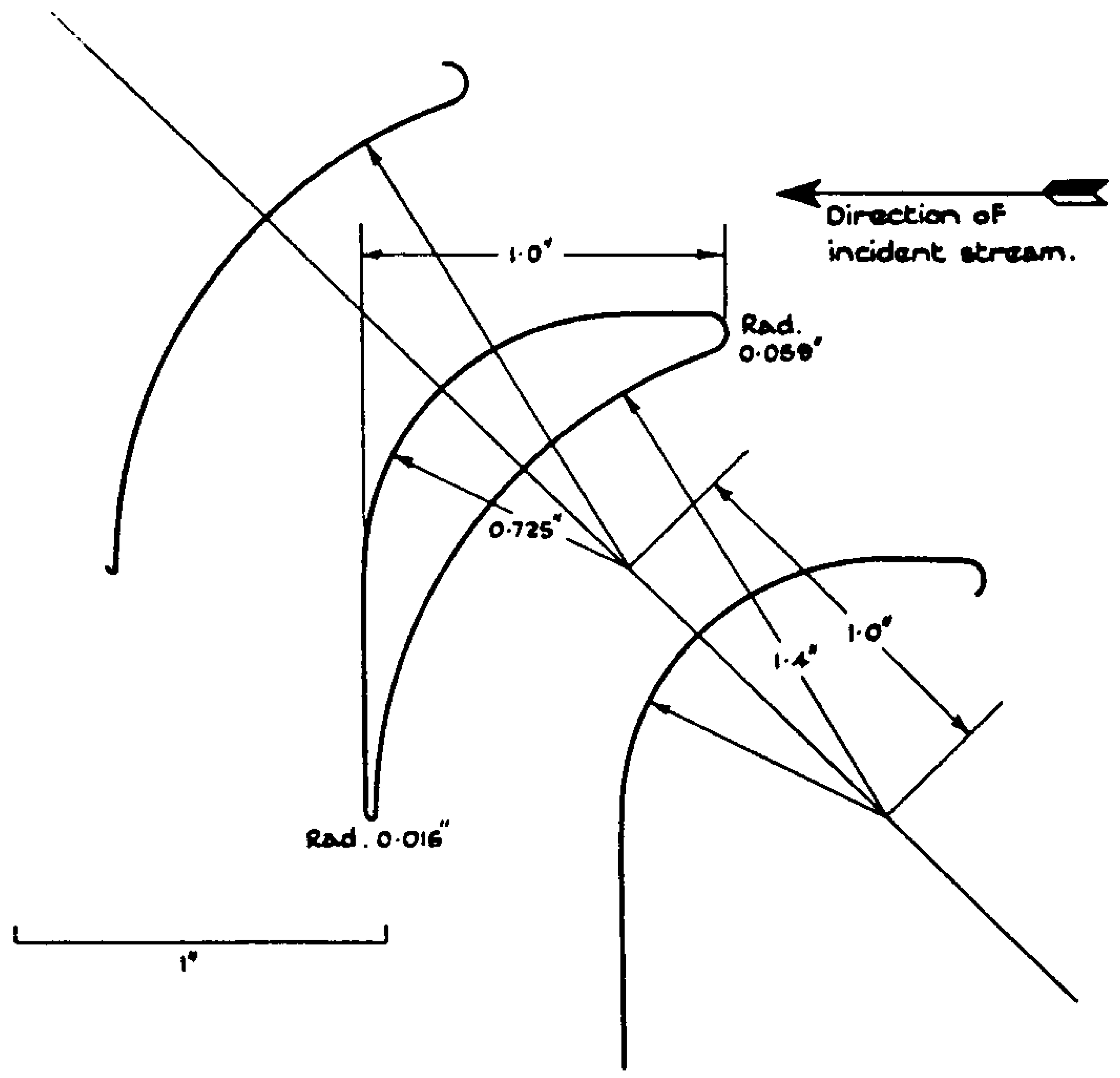

FIG. 4.—Section C.

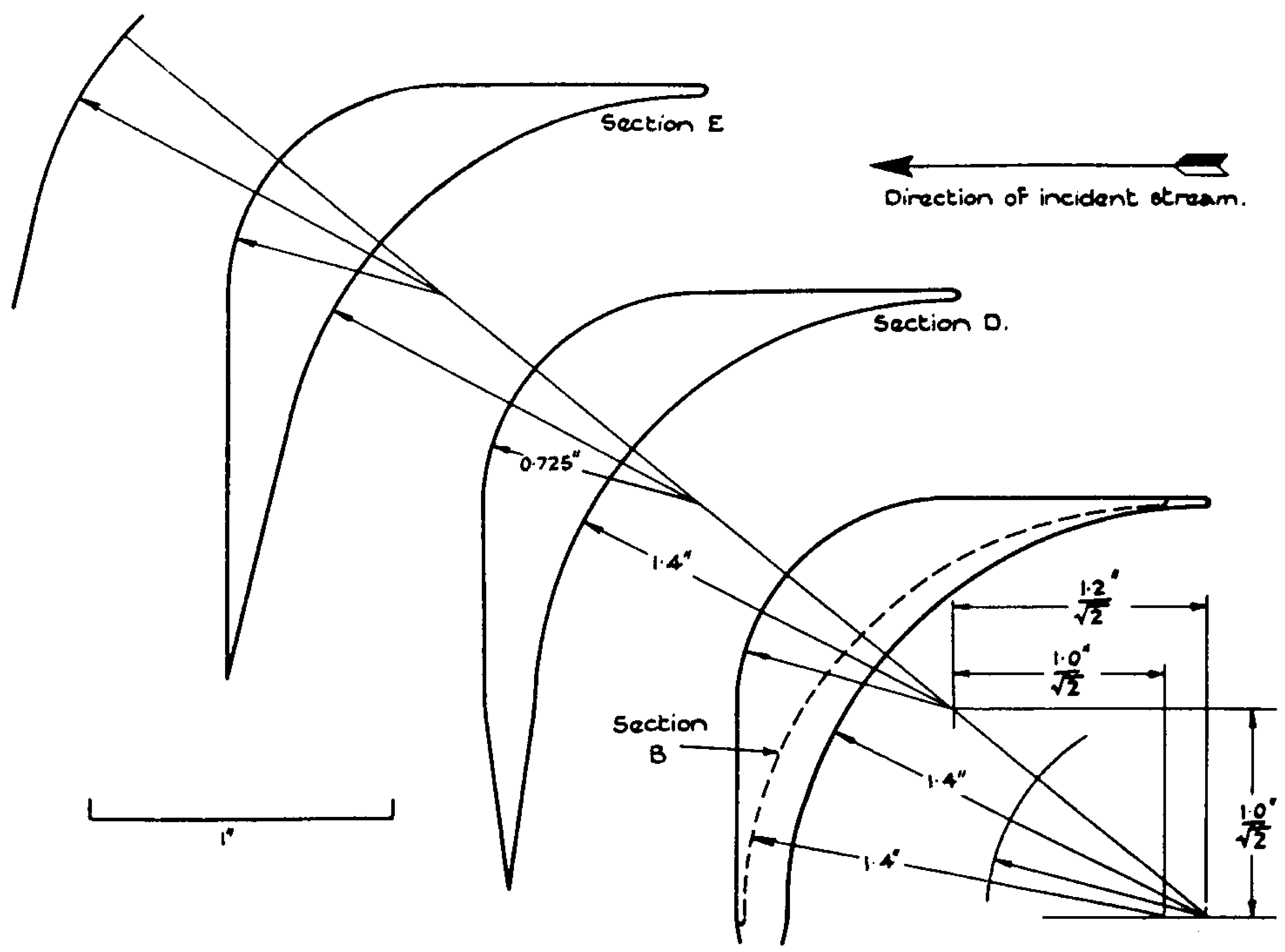

FIG. 5.—Sections D and E.

(36208) Wt. 1505/137, 6024 500 5 37 Hw. G. 377/1