REPORT No. 88

PRESSURE DROP IN RADIATOR AIR TUBES

BY

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Bureau of Standards

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RÉSUMÉ.

This report describes an investigation of effects of pressure drop in radiator air tubes, conducted for the National Advisory Committee for Aeronautics at the Bureau of Standards.

A small steel tube—0.04 inch (1 mm.) in outside diameter and 20 inches (51 cm.) long, with a static pressure opening near the center—was stretched through an air tube of a radiator and used to measure static pressure in the stream of air passing through the radiator tube. The measurements lead to the following conclusions:

1. The drop in static pressure in the air stream through a cellular radiator, and the pressure gradient in the air tubes, are practically proportional to the square of the air flow, for a given air density. The observed values of skin friction agree approximately with those found by other investigators for long pipes. These facts appear to indicate that the air flow is turbulent, even in the short tubes of the radiators.

2. The difference between head resistance per unit area and fall of static pressure through the air tubes of a radiator, noted by various observers, is shown to be apparent rather than real.

3. Radiators of different types differ widely in the amount of contraction of the jet at entrance.

4. Frictional resistance is found to be two-thirds of head resistance for one type of $\frac{11}{32}$ inch (0.87 cm.) circular cells, 5 inches (12.7 cm.) deep; and one-half of head resistance for one type of $\frac{5}{16}$-inch (0.79 cm.) square cells, 4.8 inches (12.2 cm.) deep.

5. Supplying heat to the radiator increased the pressure gradient in the tubes of one type, of ¼-inch (0.64 cm.) circular cells, 4 inches (10.2 cm.) deep, by about 15 per cent for a mean temperature difference of 110° F. (61° C.) between the water and the entering air.

INTRODUCTION.

It has been noted in the course of investigations of aircraft radiators that the drop in static pressure in the air stream between the front and rear faces of the radiator seems not to be equal to the head resistance per unit area of the section, as measured on an aerodynamic balance. In some of the earlier investigations, both in this country and abroad, an attempt was made to measure this pressure drop, and the results obtained were assumed to be equal to the head resistance per unit area of the radiator for the same air flow. But as soon as aerodynamic balances became available for the work, and actual head resistance was measured, a considerable difference was found between observed head resistance and head resistance computed from pressure drop, and no satisfactory explanation of this difference was at once apparent. Since the air emerges from the radiator in a turbulent condition, its static pressure must be measured under unfavorable conditions, and it was natural to question the reliability of the measurements taken. An attempt to measure dynamic pressure before and behind the radiator was made, but with no better success.

The investigation described in this report was accordingly undertaken, in order to make independent, and if possible more reliable, measurements of static pressure at various points in the air stream; and to throw light on the difference, if any exists, between pressure drop and head resistance per unit area.

EXPERIMENTAL METHOD.

1. *Ordinary measurements of pressure drop.*

The bulkhead tunnels used for calorimetric tests of the radiators were fitted with piezometer rings before and behind the test section.[1] In the tunnel inclosed in the steel tank these rings were 1¼ inches (3.2 cm.) from the faces of the radiator and in the "steam tunnel" there were two pairs of rings, 1¼ and 6 inches (3.2 and 15.2 cm), respectively, from the faces of the section. Readings from the 1¼ inch and the 6 inch rings were practically identical for a number of sections.

2. *Special measurements of pressure drop.*

The special measurements of pressure drop indicated in the attached curves were made in two wind tunnels: The "steam tunnel" or closed tunnel, in which the radiator core completely fills the channel; and the open tunnel, which is 54 inches in diameter, and represents conditions in free air. The measurements were obtained with the use of a small steel tube, 0.04 inch (1 mm.) in outside diameter and 20 inches (51 cm.) long, with one end closed, and a static pressure opening near the center. This tube will be referred to below as "the pressure tube." It was passed through an air cell near the center of the radiator and moved forward or backward to obtain the pressure at different points. One side of an inclined water gauge was connected to the rear end of the pressure tube and the other side to the static pressure tube of the Pitot used to measure the velocity of the air stream in the channel.

The pressure tube was supported by two pieces of piano wire which were attached to the ends, passed over crossbars set in the closed tunnel, and rings held by wires in the open tunnel—at some distance before and behind the radiator—and passed through holes in the tunnel floor, to facilitate movement forward and backward. One of the supporting wires was wound around a spool held by a ratchet, and both were kept taut by a weight of about 4 pounds (1.8 kg.) hung on the other wire. The various positions of the pressure tube were indicated by marking a point on one of the supporting wires and measuring its distance from some convenient point, such as the floor of the tunnel. In the open tunnel the positions were checked by frequent measurements (inside the tunnel) of the distance of the pressure opening from one face of the radiator; but in the closed tunnel such measurements could not be made, and only relative positions were obtained, the actual position of the radiator on the plot being estimated from the form of the curve after the latter had been drawn. Preliminary trial showed that consistent results could be obtained with only ordinary care in centering the pressure tube inside of the radiator air cell. In the different sections used the pressure tube occupied between 1 and 3 per cent of the area of the cell through which it passed.

In most cases water was not passed through the radiator sections, and they were at the same temperature as the air; but in one case—type C–9, ¼-inch (0.64 cm.) circular cells 4 inches (10.2 cm.) deep—after the section had been used at room temperature hot water was pumped through it as in regular calorimetric tests, and a mean temperature difference of about 110° F. (61° C.) was maintained between the water and the entering air.

3. *Computation.*

In the closed tunnel the airflow was expressed in pounds per second per square foot of tunnel section (or of radiator core), and pressure difference was expressed in pounds per square foot. Previous work in a wind tunnel under partial vacuum has shown that pressure drop between piezometer rings before and behind the radiator is inversely proportional to the air density at the front ring, for a given mass flow of air; and proportional (very nearly) to the square of the mass flow of air, for a given density. These two relations were used to reduce the observations to a common density, and to correct for small variations in air flow. Observations were taken at from three to six air velocities on each section.

In the open tunnel pressure drop was expressed in pounds per square foot, as before, but the air flow was expressed in miles per hour of the stream through the tunnel, and the corresponding mass flow of air through the radiator was computed from the relation between these

[1] The two tunnels are described in detail in Technical Report No. 60.

two quantities previously found in the regular tests of the radiator.[2] Correction for air density was made as explained in Technical Reports Nos. 60 and 63, for measurements in the open tunnel, and corrections for small variations in velocity was made on the assumption that pressure drop, like head resistance, is proportional to the square of the air velocity. Observations were taken at only one velocity on each section, except that in the case of the Spery type 10 velocities were used with each of two positions of the pressure tube, and the results showed the assumed relation between pressure drop and velocity to be approximately true.

It was found, however, that the pressure gradient along the tube of the radiator seemed not to be the same in the open and closed tunnels for the same mass flow of air and the same density, and this difference was interpreted as indicating an error in the measurement of either the pressure gradient or the air flow. The measurement of the air flow was known to be subject to errors as high as 3 to 5 per cent in different radiators, and it appeared reasonable to regard the pressure gradient within the tube as a good indication of the air flow. Accordingly, for comparison of data obtained in the two tunnels, the results were reduced not to the same air flow as indicated by the usual measurements, but to the same pressure gradient in the tubes (this gradient being proportional to the square of the air flow), and this condition was taken to represent equality of air flow in the two tunnels. The differences between the air flows previously computed and those given by this procedure were from 5 to 8 per cent.

DESCRIPTION OF CURVES.

In the accompanying curves pressure drop in pounds per square foot is plotted against distance along the axis of the air tube of the radiator, the distance being measured in inches forward and backward from the rear face of the section. The location of the two faces are indicated by heavy dotted lines; and for each of the three sections tested in both the open and closed tunnels, head resistance corresponding to the indicated air flow is shown by a solid vertical line marked "R."

Plots 1–5 show results of tests in the closed tunnel, and in plots 6–8 results of tests in the open tunnel are shown, with the closed tunnel curves of equal pressure gradients superposed upon those of the open tunnel.

Plot 2 shows the effect of imparting heat to the air as it goes through the radiator. In this case the mean temperature difference between the water in the radiator and the entering air was about 110° F. (61° C.).

Plot 3 gives a comparison of pressure drop in two radiators whose tubes are of very nearly the same dimensions, but with different conditions of surface. In one (C–10) the cooling surfaces (walls of the air tubes) were very rough, and in the other (C–9) they were somewhat smoothed, though not highly polished.

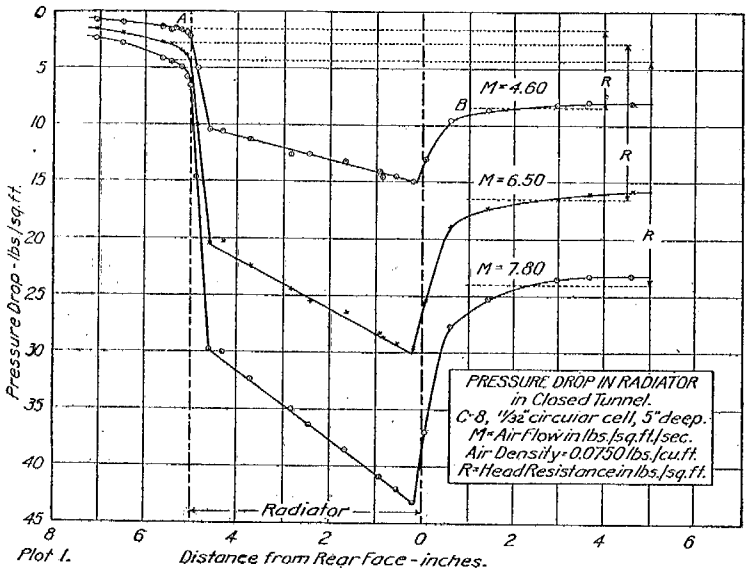
It will be noted that plots 5 and 8, representing the Spery type (illustrated in the photographs, figs. 9 and 10), are plotted on twice the scale used for the other sections, in order to show clearly the loops in the curves as they follow the four constrictions in the air tubes.

DISCUSSION OF RESULTS.

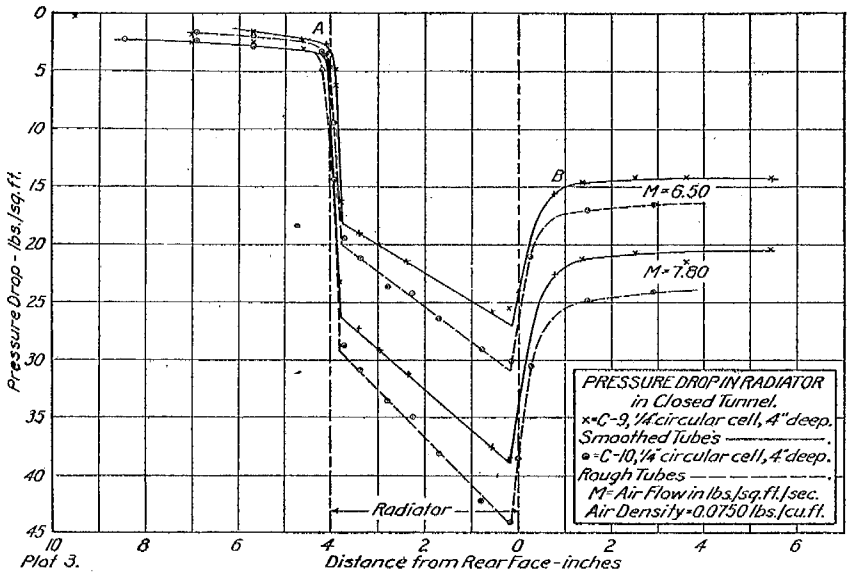
1. The pressure measurements were of course made under unfavorable conditions, and the results obtained should be used with a little caution, but the consistency of the observations seems to indicate a fair degree of reliability, and a comparison of pressure gradients in the three radiators with circular cells shows a reasonable agreement with values of skin friction found for long tubes by Stanton & Pannell, Saph & Schoder, and others, the values here obtained being slightly higher than those of the other observers, for smooth tubes.

2. The drop in pressure in the air stream through the radiator and the pressure gradient in the tubes are practically proportional to the square of the air flow, for a given air density. This fact and the approximate agreement of observed skin friction with that found by other investigators appear to indicate that there is turbulent flow in the short tubes of the radiators.

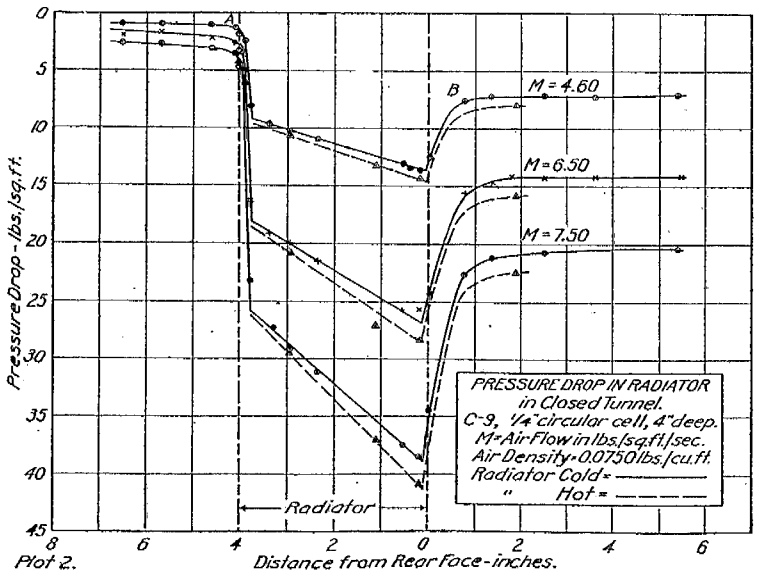
[2] The regular measurement of mass flow of air was made with a special air Venturi meter, described in Technical Report No. 60.



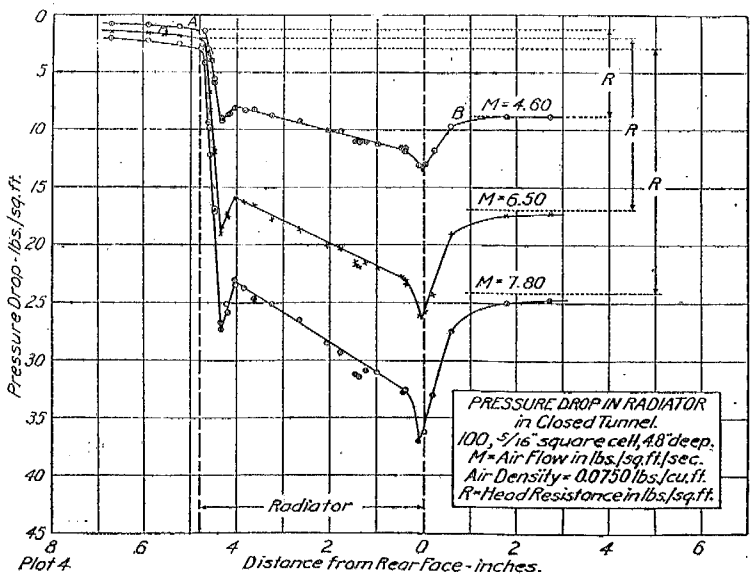
Plot 1.



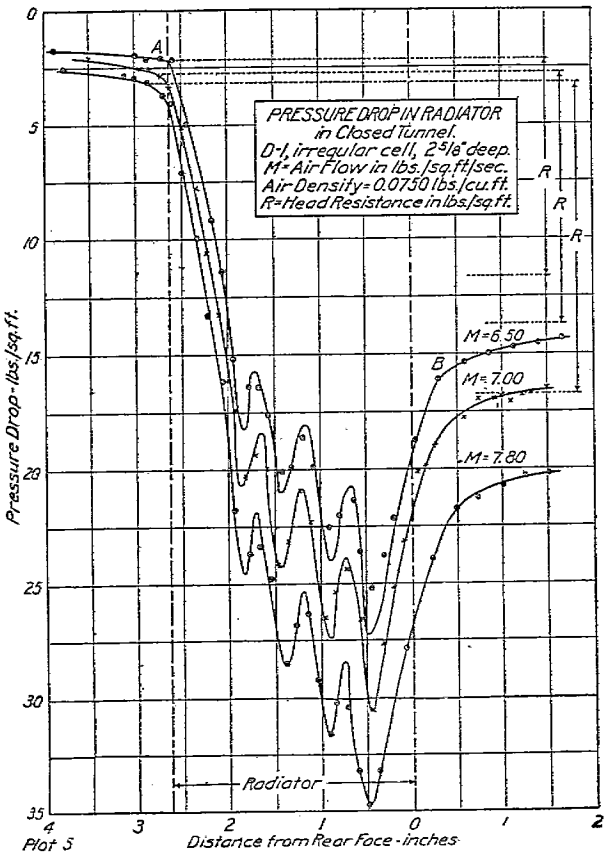
Plot 3.



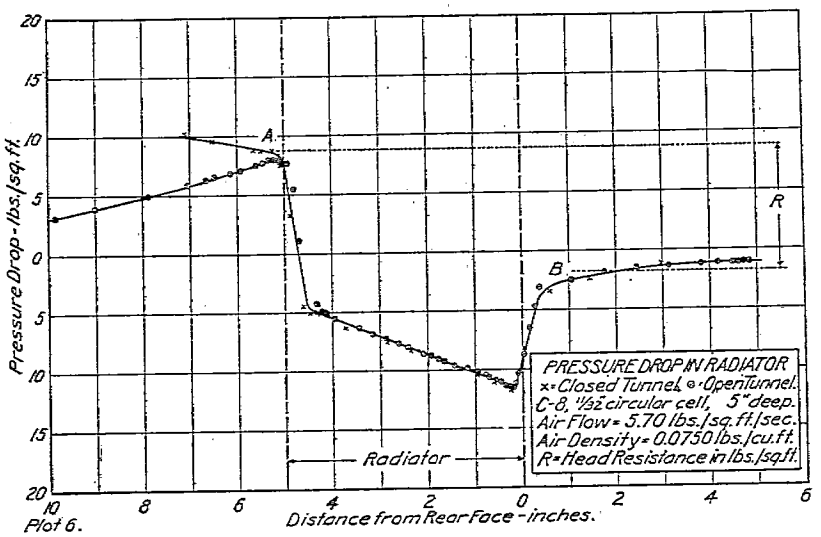
Plot 2.



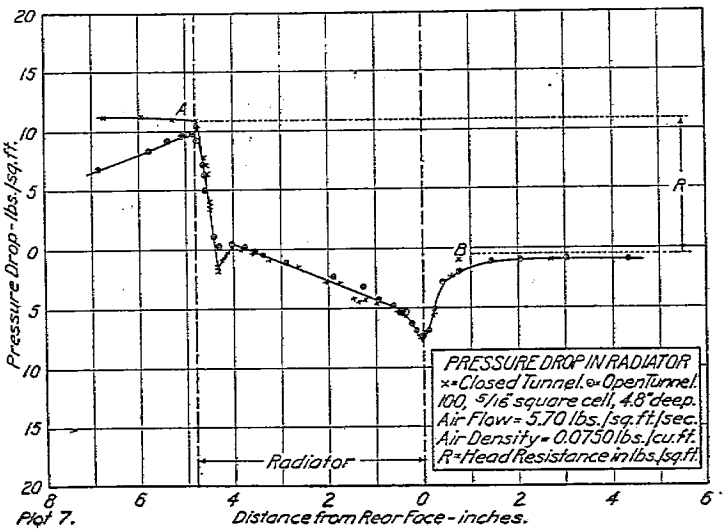
Plot 4.



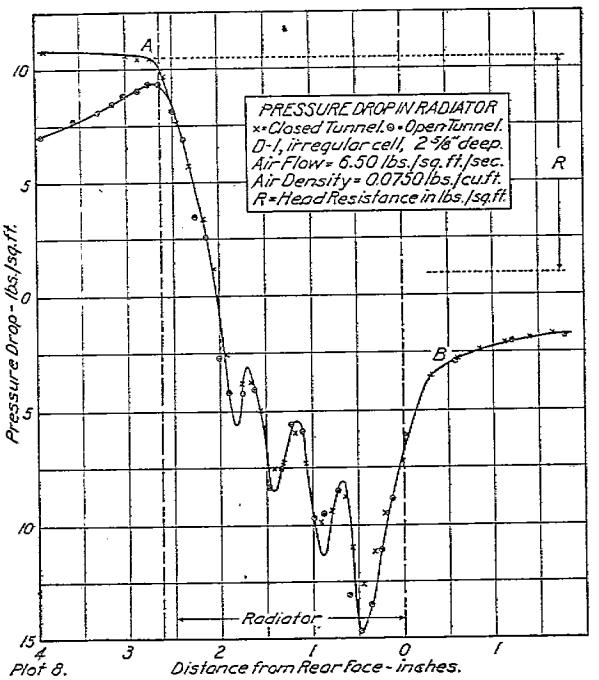
Plot 5



Plot 6.



Plot 7.



Plot 8.

3. The results seem to indicate that the differences formerly observed between pressure drop and head resistance per unit area were apparent rather than real, for the present measurements fail to show convincing evidence to prove that pressure drop is unequal to head resistance per unit area, provided the former is measured at such sections across the air stream as will eliminate the effects of changing velocity at entrance and exit of the radiator. On the other hand, the curves show clearly that if pressure drop is measured between two piezometer rings 1¼ inches (3.2 cm.) from the faces of the radiator (as in the tunnels described), the result will be a value somewhat higher than the head resistance per unit area, and the discrepancy will be greater for some types of core than for others; for in some radiators the high-velocity jets issuing from the tubes persist for a greater distance than in others, before uniform distribution of flow across the channel is regained. In the earlier work, the air flow through the radiator was used as a basis for comparison between pressure drop and head resistance, and errors in the measurement of air flow through the core in the open tunnel are responsible for some of the discrepancies noted; because the measurement of air flow is attended with some difficulty, and is subject to errors that appear to run as high as 8 per cent, and which lead to errors in head resistance about twice as great, since head resistance is proportional to the square of the air flow.

4. A comparison of the curves for the types C–8 and No. 100 indicated a marked difference between radiators in the amount of contraction of the jet at entrance and exit. The type C–8 is made of circular cells expanded to hexagonal form at the ends, and the transition from one form to the other furnishes a very crude streamline form, but one that is much better than that of the type No. 100, which is made with square cells, the ends of the water tubes being merely pressed together to form a joint, with no approach to a streamline form. The difference in the form of the curves for these two types is doubtless due in part to this difference in form of entrance, and also in part to the fact that one has circular and the other square cells. If, in the curves for No. 100, the loops at entrance and exit are interpreted as representing the contraction of the jet, and if it is assumed that the air stream fills the tube in the part for which the pressure curve is straight, Table II shows that the tube is filled for only about 82 per cent of its length. Whether this condition indicates that 82 per cent of the walls of the tubes is scoured by the air stream, and the remaining 18 per cent covered by air that is turbulent but not rapidly changed, is a question that must be postponed until more is known about the conditions of turbulent flow in the radiator tubes.

5. If it is assumed that the loss of head in the part of the tube for which the pressure curve is straight is due to skin friction, Table I shows that the frictional loss is two-thirds of the head resistance for C–8—$\frac{11}{32}$-inch (0.87 cm.) circular cells, 5 inches (12.7 cm.) deep—and one-half of the head resistance for No. 100—$\frac{5}{16}$-inch (0.79 cm.) square cells, 4.8 inches (12.2 cm.) deep.

6. The effect of supplying heat to the radiator is to increase the pressure gradient and the pressure drop between the front and rear faces, the gradient being increased by about 15 per cent in the case of the type C–9—¼-inch (0.64 cm.) circular cells, 4 inches (10.2 cm.) deep—for a mean temperature difference of 110° F. (61° C.) between the water in the radiator and the entering air.

The statement has been made by other investigators that increase in head resistance due to temperature difference can be computed from the increase in momentum of the air as it is heated and consequently made less dense; and it may be well to point out that while such reasoning may apply to pressure drop for a given air flow through the radiator, there is some question about its applicability to head resistance at a given airplane speed.[3] The expansion of the air while it is being heated in the radiator tube tends to do two things: To push the air out from the rear face at a higher velocity than it had at entrance; and to develop a back pressure, acting against the pressure that drives it through the tube. This back pressure tends to retard and reduce the air flow, and by so doing, to decrease the skin friction and consequently

[3] In considering this problem, it must be borne in mind that there are two speeds concerned—the rate of flow of air through the radiator, which may be expressed in pounds per second per square foot of frontal area; and the linear velocity with which the radiator may be regarded as passing through still air. The comparisons made throughout this report are based on equal rates of flow through the radiator.

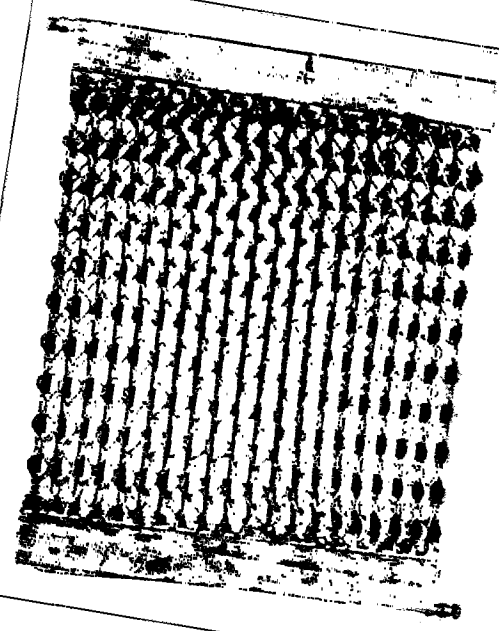


FIG. 9.

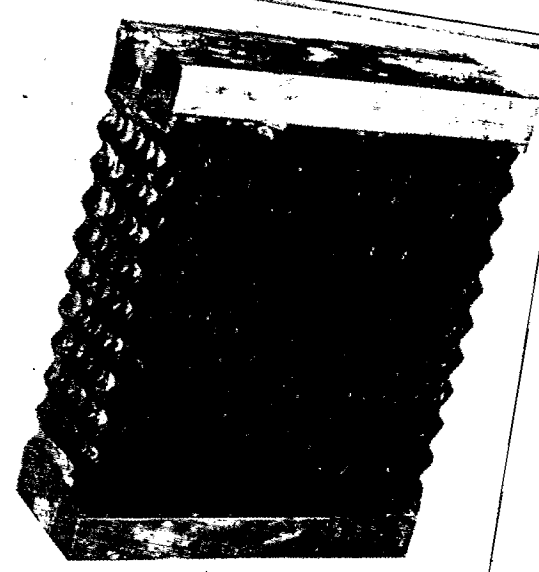


FIG. 10.
Spery radiator. See plots 5 and 8.

the head resistance. On the other hand, a decrease in air flow through the radiator requires that a greater part of the approaching air shall be deflected around it, and this condition tends to increase the head resistance. Until experimental evidence is available, the question of the effect of temperature difference on head resistance will be left open.

TABLE I.—*Mass flow of air is in lb. per sec. per sq. ft. frontal area.*

Radiator.	Mass flow of air.	Gradient, lb./ft.² per in.	Length over which gradient is uniform, in.	Friction loss, lb./ft.²	Head resistance, lb./ft.²	Friction loss as % of H. R.
C-8	4.60	1.02	4.3	4.4	6.9	64
	5.70	1.57		6.75	10.5	64
	6.50	2.16		9.3	13.7	68
	7.00	2.46		10.6	15.9	67
	7.80	3.02		13.0	19.7	66
Mean						66
No. 100	4.60	1.02	3.6	3.7	7.4	50
	5.70	1.58		5.7	11.3	50
	6.50	1.95		7.0	14.7	48
	7.00	2.27		8.2	17.0	48
	7.80	2.60		9.4	21.1	45
Mean						48
C-9 (cold)	4.60	1.19	3.6	4.3		
	5.70	1.79		6.45		
	6.50	2.40		8.65		
	7.00	2.67		9.6		
	7.80	3.60		13.0		
C-10	5.70	2.67	3.5	9.3		
	6.50	3.03		10.6		
	7.00	3.46		12.5		
	7.80	4.00		14.0		

TABLE II.

	C-8.	No. 100.
Depth of radiator ... inches	5.0	4.8
Length of air tube ... do	4.6	4.4
Length over which gradient is uniform ... do	4.3	3.6
Per cent of tube length over which gradient is uniform	94	82

TABLE III.—*Effect of heat, radiator C-9.*

Air flow.	Gradient.		Per cent increase.
	Cold.	Hot.	
4.60	1.19	1.35	13
5.70	1.79	1.97	10
6.50	2.40	2.78	16
7.00	2.67	3.18	19
7.80	3.60	4.14	15
Mean			15