NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 674

COOLING ON THE FRONT OF AN AIR-COOLED ENGINE CYLINDER IN A CONVENTIONAL ENGINE COWLING

By M. J. BREVOORT and U. T. JOYNER

1939

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s² or 32.1740 ft./sec.²

m, Mass $=\frac{W}{g}$

I, Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $=\frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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Langley Memorial Aeronautical Laboratory

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By M. J. Brevoort and U. T. Joyner

SUMMARY

Measurements were made of the cooling on the fronts of model cylinders in a conventional cowling for cooling in both the ground and the cruising conditions. The mechanisms of front and rear cooling are essentially different. Cooling on the rear baffled part of the cylinders continually increases with increasing fin width.

For the front of the cylinder, an optimum fin width was found to exist beyond which an increase in width reduced the heat transfer.

The heat-transfer coefficient on the front of the cylinders was larger on the side of the cylinder facing the propeller swirl than on the opposite side. This effect became more pronounced as the fin width was increased. These results are introductory to the study of front cooling and show the general effect of the several test parameters.

INTRODUCTION

Most of the information available regarding cooling on the front of a cylinder of a radial air-cooled engine has been obtained from wind-tunnel tests on an unbaffled section of a cylinder. The nature of the air flow within the front of a conventional N. A. C. A. cowling was shown in reference 1 to be very different from the steady flow obtained in a free air stream; it is therefore probable that the cooling will be very different for the two conditions. There is every reason to believe that front cooling will not show the same dependence on fin spacing and fin width for the peculiar air-flow conditions found in the front of a cowling as for the baffled part of the cylinder.

The advisability of baffling the entire cylinder and resorting to blower cooling should not be admitted until front cooling in a conventional cowling has been exhaustively studied. The details of the mechanism by which front cooling is accomplished and the power expended for this cooling will be discussed in this report.

In reference 2 it was shown that an engine nacelle of 52-inch diameter in an air stream of 100 miles per hour had 32 pounds drag with a hemispherical nose, 42 pounds drag with a flat plate in the nose, and 45 pounds with the nose open. The tests for all three arrangements were made with the skirt closed, which gave no air for cooling. It is thus seen that, at 100 miles per hour, about 13 pounds more drag can be expected with an open nose than with a streamline nose. All these values were reduced when a nacelle having a better afterbody was tested. The best value for the difference between a good conventional nose and a streamline nose now appears to be only one-fifth of the value of 13 pounds given in reference 2.

It was shown in reference 3 that the order of the cost of cooling the rear of the cylinders is 1 to 1½ percent of the engine power for a representative engine. Inasmuch as the power cost of cooling the front of the cylinders is independent of the power of the engine enclosed in the cowling, this front cooling power will amount to only about 1 percent of the power of a 2,000-horsepower engine at 300 miles per hour. Thus, the total power required for cooling would amount to not more than 2½ percent of the brake horsepower of a large engine. If the wing has a thickness comparable with the engine diameter, the form drag will disappear almost entirely and the power cost of the engine installation will be close to the power cost of cooling.

It was further found (reference 2) that the cooling of the front of the cylinders compared quite favorably with the cooling of the rear baffled part of the cylinders in spite of the fact that no directed air velocity could be measured over the front of the cylinders. Hot-wire measurements showed about 70 percent as much cooling in the front of the engine as in the free air stream. The open nose, which contributes about 3 pounds drag at 100 miles per hour, therefore gives very satisfactory front cooling. Since this drag increases proportionally with the dynamic pressure and since the cylinder finning must be adequate to give satisfactory cooling of the engine at the climbing speed, it is obvious that, at the cruising speed, much more power is required and more cooling is realized than is necessary on the front of the cylinders.

On the ground and to a lesser extent in the take-off, almost no positive pressure exists in the front of an open-nose cowling. The factors affecting the pressure in the front of the cowling are explained in reference 1 for the ground condition. It was shown that, when the hub and the propeller shank had no blade section, the pressure developed by the blade sections near the outer edge of the cowling opening was largely lost by

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the hub section. By the use of propellers with blade sections close to the hub or by the use of spinners, a pressure was maintained over the front of the engine. The most practicable arrangement was a fixed disk set behind the propeller, which left an annular opening between the inner edge of the cowling and the outer edge of the disk with sufficient open area to allow the entry of the air without an appreciable energy loss. This annular opening must be behind a working section of the propeller and, for the case of ground cooling, large-diameter openings are preferable. The forward or backward position of the disk had a marked effect on the pressure developed.

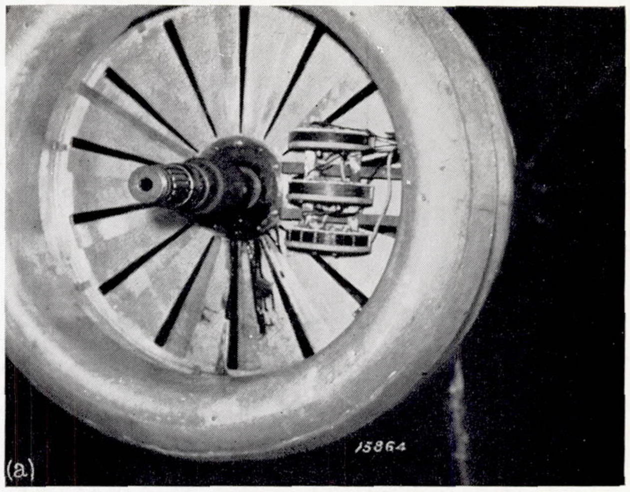
An effect on the pressure developed, resulting from a change with air speed of the configuration of flow around the cowling, was found on nose 7 and spinner 10 (reference 4). In the particular arrangement reported in reference 4, the air flow around the cowling changed with the speed in such a manner as to give a high $\Delta p/q$ in the take-off condition and a relatively low $\Delta p/q$ at a high speed. It is probable that a spinner, adjustable forward and backward, employed behind the propeller might be a practicable means of controlling the front pressures and the front cooling. It is further shown in reference 1 that, when the airplane is on the ground, a swirl exists in the front of the engine; this swirl depends upon the propeller speed, the diameter of the cowling, and the engine conductivity.

The mechanism of rear cooling and the means of obtaining the maximum cooling at the rear have been described in references 2, 5, 6, and 7. These reports show the power for cooling and how this power can be most usefully employed by the choice of optimum baffle shape and baffle length for the fin spacing used. They also point out how much the cooling can be improved by decreasing the fin spacing.

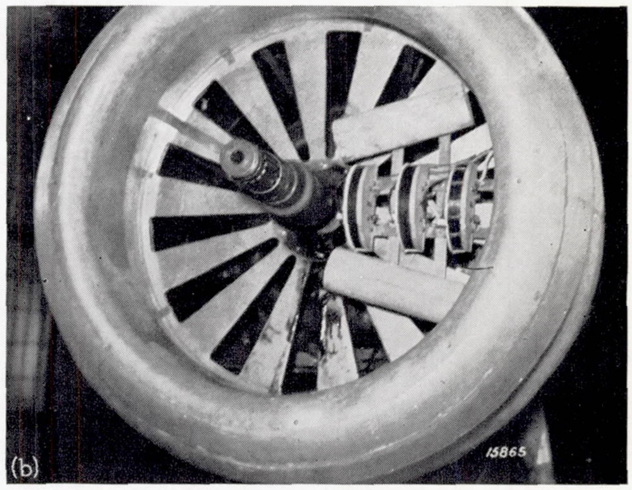
The present report gives the results of a study to determine the cooling in the front of an engine cowling for the ground and the cruising conditions at various locations within the cowling with and without a spinner; several fin spacings and fin widths were used. A knowledge of the distribution of cooling ability within the cowling is also required and this knowledge is obtained from the same measurements used to determine the effect of fin dimensions on cooling and the effect of operating conditions on cooling.

APPARATUS AND METHODS

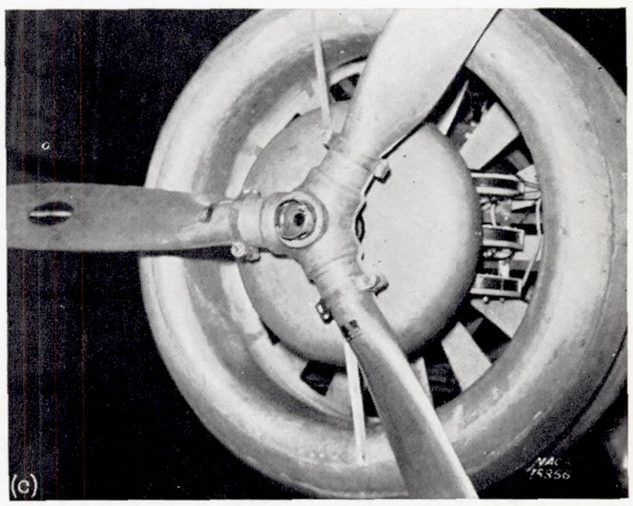
All the tests were made in the nose of a full-scale cowling-nacelle combination in the N. A. C. A. 20-foot tunnel. The diameter of the opening in the front of the cowling was 35 inches. The engine was represented by a baffle plate of variable opening (fig. 1 (a) and (b)) to simulate engine conductivities ranging from 0 to 0.116.



(a) Test cylinders in place; engine conductivity, 0.037.



(b) Test cylinders and wooden cylinders in place; engine conductivity, 0.116.



(c) Test cylinders, 24-inch round-edge disk, and propeller in place; engine conductivity, 0.116.

FIGURE 1.—General views of test set-up.

Propeller E was used for all the tests. It has Navy plan form 3790; the hub sections are shown in figure 1 (c).

Eight half cylinders, similar to the one shown in figure 2, were made of brass to the dimensions given in table I. The diameter at the base of the fins was 5.81 inches and the thickness of the wall was ⅛ inch for all cylinders. The length of each cylinder was approximately 1 inch and the inside diameter was 5.56 inches. The fin thicknesses desired in these cylinders were estimated, from the values given in reference 7, for the optimum thickness for the maximum cooling of the baffled part of a cylinder. No information being available regarding optimum thickness for maximum cooling of a cylinder in an open cowling, the use of these values is permissible because the fin thickness is not a very critical quantity.

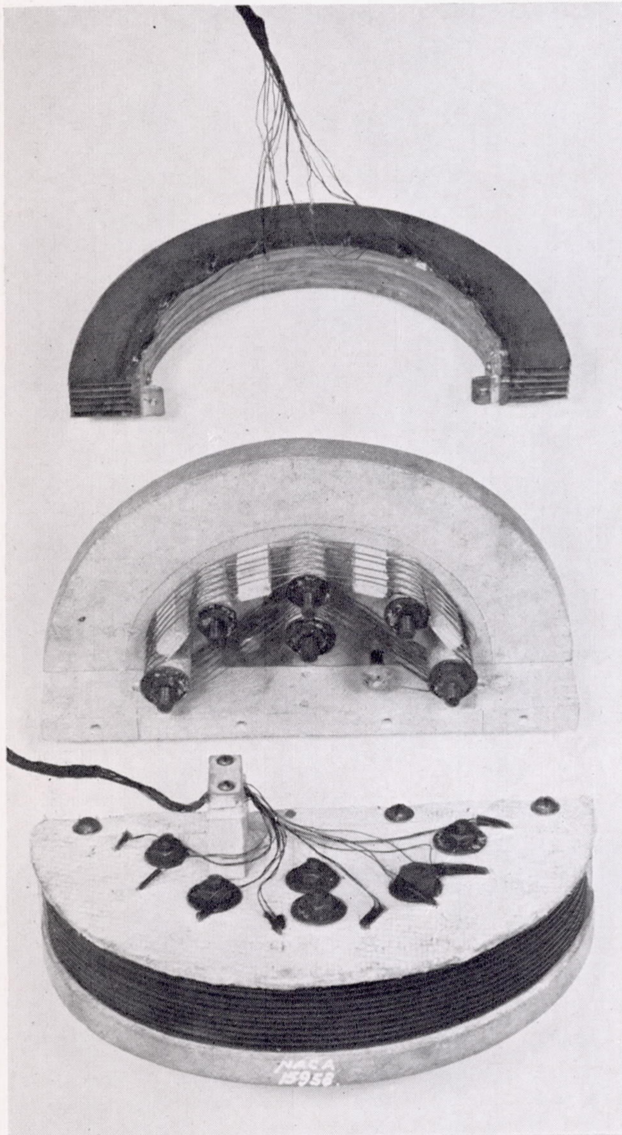


FIGURE 2.—Detailed view of test cylinder.

TABLE I
CYLINDERS TESTED

Cylinder	Fin width (in.)	Fin spacing (in.)	Fin thickness (in.)	Number of fins on cylinder	Length of cylinder (in.)	Area 9.13× length (sq. in.)
I	0.5	0.031	0.012	23	1.083	9.88
II	.5	.062	.016	12	.980	8.95
III	.5	.125	.021	7	1.062	9.68
IV	1.0	.031	.016	21	1.045	9.53
V	1.0	.062	.025	12	1.110	10.12
VI	1.0	.125	.033	6	.955	8.72
VII	2.0	.062	.031	11	1.050	9.57
VIII	2.0	.125	.040	6	1.020	9.30

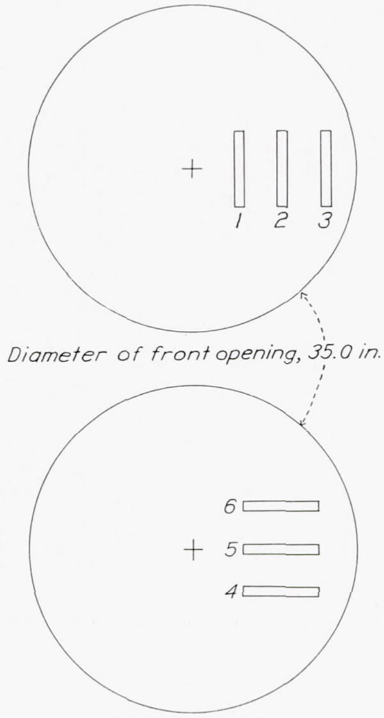


FIGURE 3.—Positions in which cylinders were tested.

Eight thermocouples were sunk into the middle of the cylinder wall at equal intervals around the circumference and welded to the cylinder. The temperature of the cylinder wall was determined by measuring the thermocouple electromotive force with a potentiometer. By this method, temperatures could be measured with an accuracy of about ±0.3° F.

Each test cylinder was mounted on a heating unit (fig. 2) to form a complete test unit, also shown in figure 2. All tests were made with three of these test units mounted on a bracket. (See fig. 1 (a).) The three heating units were made from the same kind of wire and had the same resistance. Current was passed through the three heating units in series so that equal quantities of heat were generated in the three test units. About 275 watts were dissipated in each unit.

The six positions in which the cylinders were tested are shown in figure 3; the cylinders mounted in these positions are shown in figure 1 (a) and (b).

In order to reproduce as closely as possible the actual conditions of air flow over the front of an engine, two wooden cylinders 4 inches in diameter were mounted as shown in figure 1 (b) for most of the tests with the cylinders in positions 1, 2, and 3.

A round-edge disk (fig. 1 (c)) 24 inches in diameter was designed according to the information given in reference 1 so that its size would be optimum for an engine conductivity of 0.100

The values of $\Delta p/q$ obtained in the cruising condition were 2.2, 1.8, 1.6, and 1.4 for conductivities of 0, 0.037, 0.078, and 0.116, respectively.

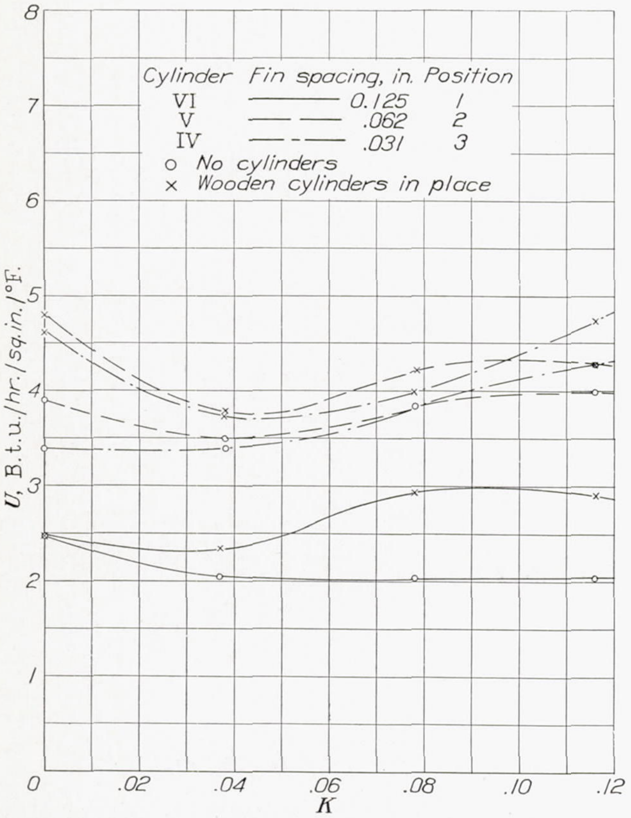


FIGURE 4.—Variation of average heat-transfer coefficient with engine conductivity for three cylinders, with and without wooden cylinders in place. Ground run.

METHOD OF CALCULATING OVER-ALL HEAT-TRANSFER COEFFICIENT

The average cylinder-wall temperature was obtained by taking the arithmetic mean temperature of the eight thermocouples in the cylinder wall. This mean temperature, together with the cylinder-base area and the heat input per hour, makes it possible to calculate U as follows:

$$U=\frac{0.75H}{A(t_m-t_a)} \tag{1}$$

where

U is the over-all heat-transfer coefficient, B. t. u. per hour per square inch wall area per °F.
H, heat input per hour, B. t. u. per hour.
A, cylinder-wall area, square inches.
t_m, mean temperature of the cylinder wall, °F.
t_a, free-air temperature, °F.

The factor (0.75) in the numerator of equation (1) was introduced to take into account the heat lost through the asbestos end plates and base. This factor was determined as a good average value from experiments with one of the test units. In the experiments made to determine these values, the temperature and the quantity of the air heated by the fins were measured separately from that of the air heated by the asbestos, and the heat given to each was determined.

GROUND COOLING

The results of the ground tests are presented in figures 4 to 10. These figures show the variation of the average over-all heat-transfer coefficient U with engine conductivity K for the particular conditions tested.

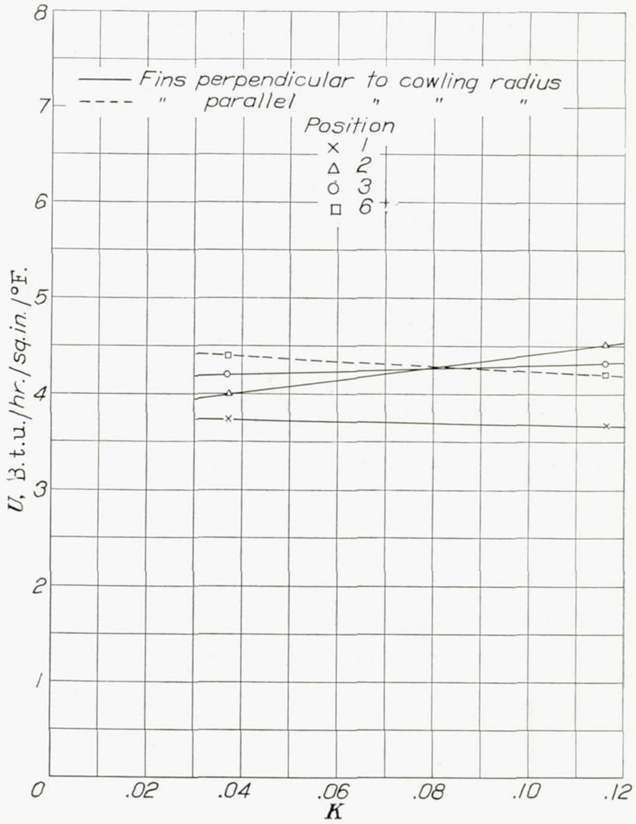
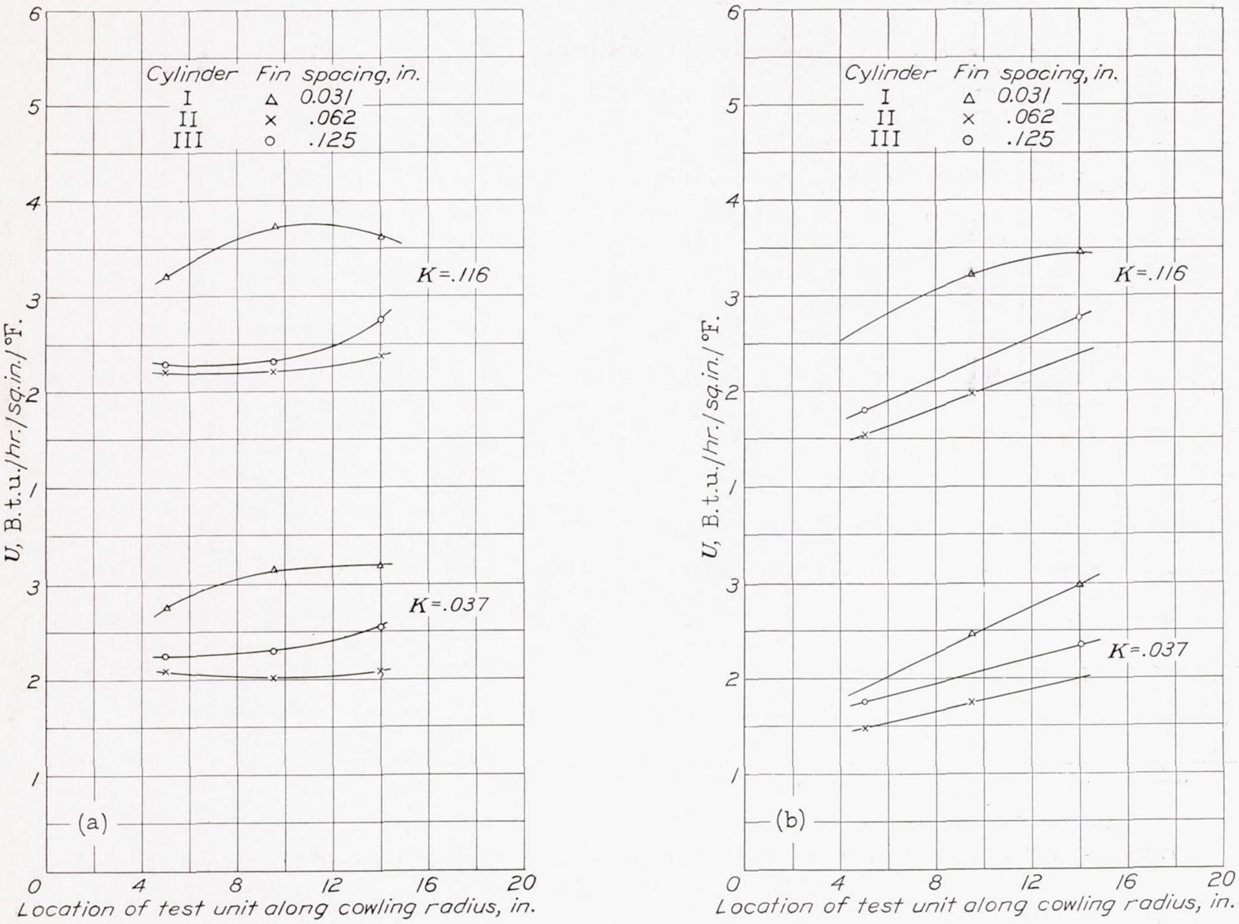


FIGURE 5.—Variation of average heat-transfer coefficient with engine conductivity for cylinder V in three test positions. Ground run.

Most of the ground-cooling tests were made with the propeller operating at 985 r. p. m. In a few of the tests, from which the values shown in figures 6 (a), 6 (b), and 7 were calculated, the propeller was operated at 900 r. p. m. All such tests were made at zero air speed.

The effect of the addition of the two wooden cylinders (fig. 1 (b)) on the cooling of the test cylinders (fig. 4) is to increase the cooling somewhat in all cases tested, the increase in cooling being about the same for each cylinder.



(a) No disk.

(b) 24-inch round-edge disk.

FIGURE 6.—Variation of average heat-transfer coefficient with location along the cowling radius for three cylinders having ½-inch fin width tested in positions 1, 2, and 3. Ground run.

The variation in cooling along the front of a cylinder barrel from base to head (figs. 5 and 6 (a)) is shown to be small in an open-front cowling for the ground-cooling condition. Cooling on the cylinder head, which corresponds roughly to cooling in positions 4, 5, and 6, is of the same order as cooling on the barrel in the open-front cowling. This relation may be seen by comparing figures 6 (a) and 7 and also by examining figure 5. From the results shown by these figures, it can be said that the position of the test cylinder in the cowling and its orientation with respect to the propeller swirl are not so important as fin spacing and width in determining front cooling for the ground condition.

The effect of adding the round-edge disk in front of the cowling (fig. 1 (c)) varies from a slight increase to a 20-percent decrease in cooling. This variation can be seen by referring to figures 8 and 9 and by comparing figures 6 (a) and 6 (b).

In position 3, the test cylinder is exposed to the air flow coming through the slot between the disk and the cowling, and the cooling is as good as or slightly better than the cooling in an open-nose cowling. (Cf. figs. 6 (a) and 6 (b) and see figs. 8 (a) and 9 (a).)

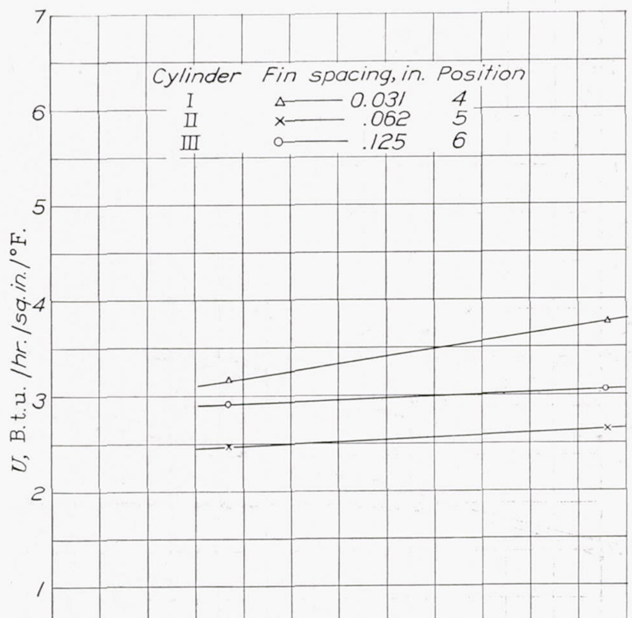
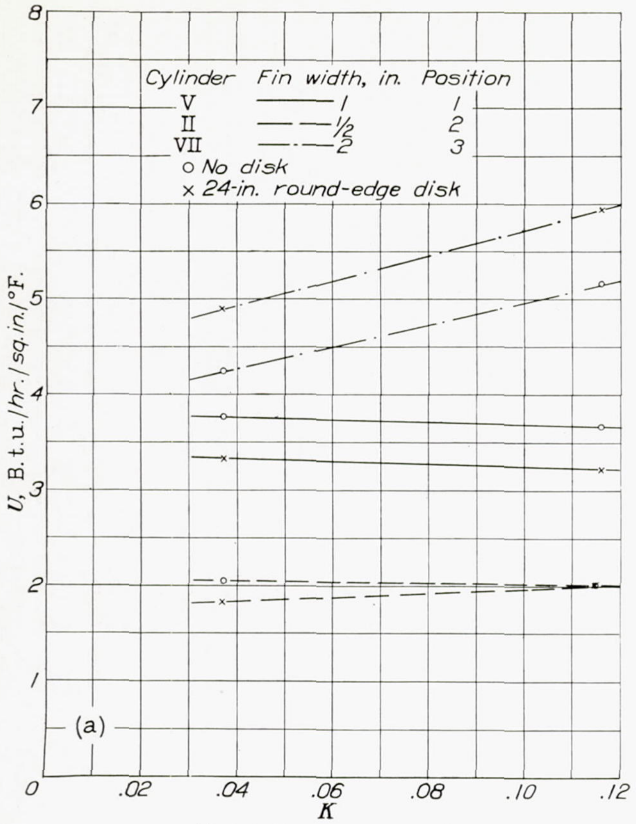
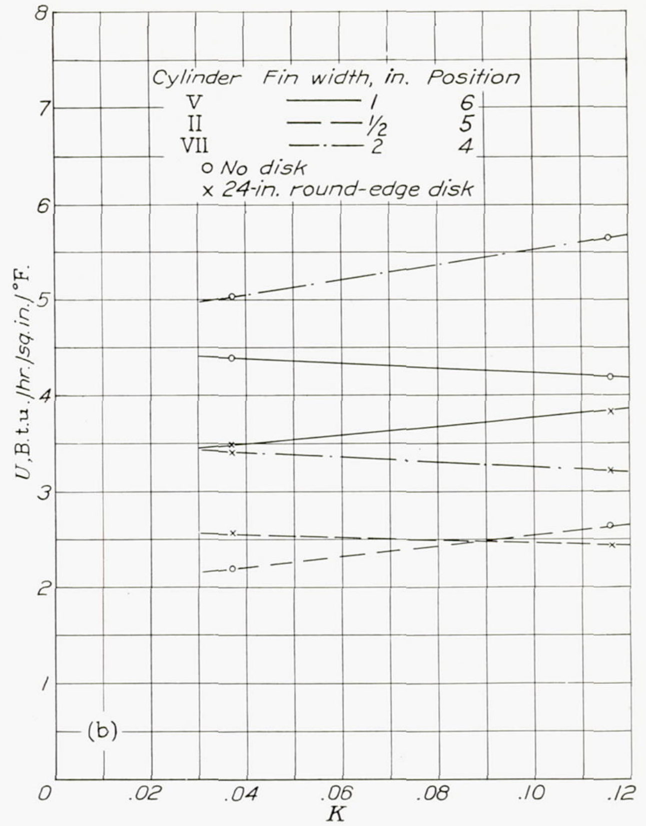


FIGURE 7.—Variation of average heat-transfer coefficient with engine conductivity for three cylinders having ½-inch fin width tested in positions 4, 5, and 6. Ground run.

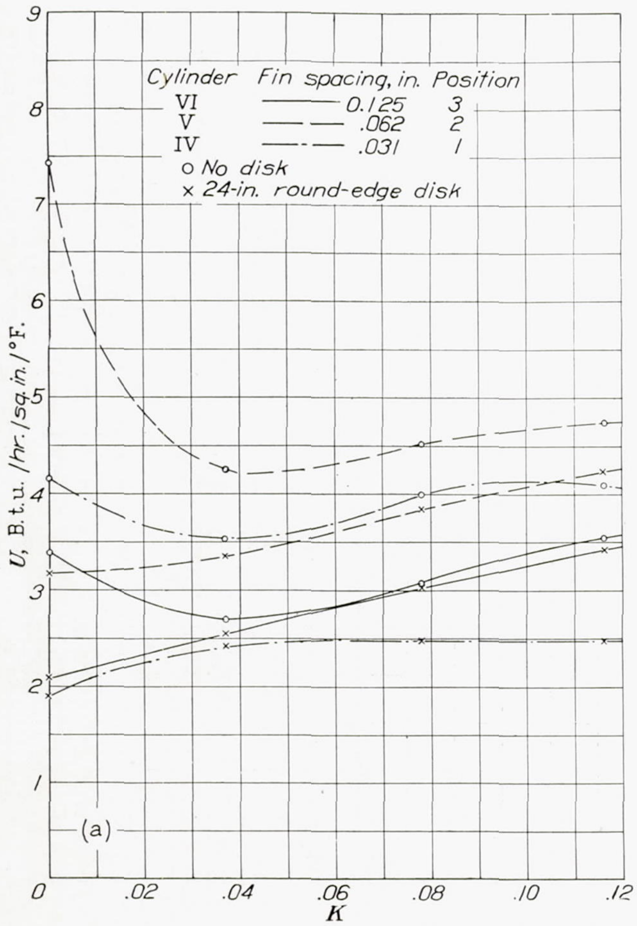


(a) Tested in positions 1, 2, and 3.

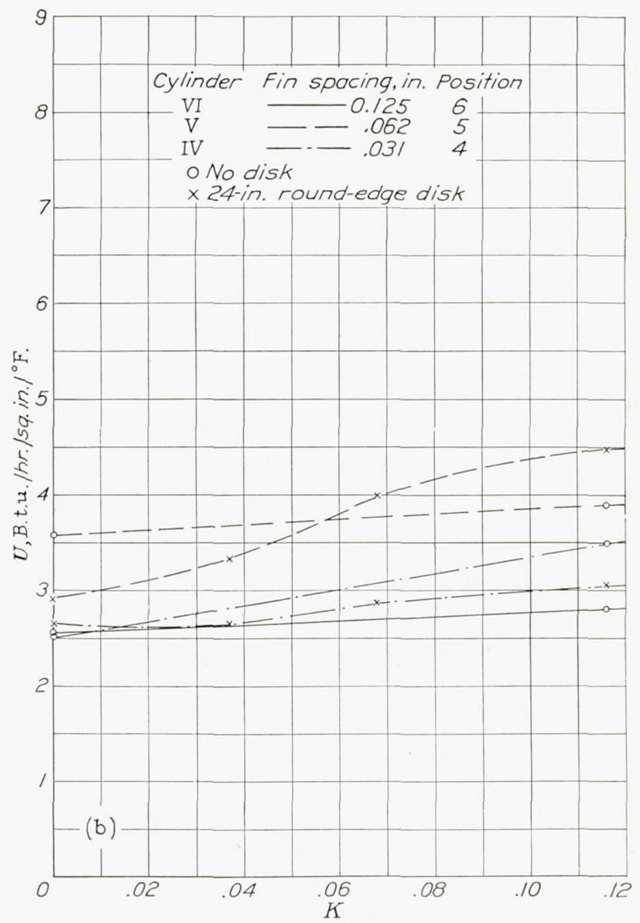


(b) Tested in positions 4, 5, and 6.

FIGURE 8.—Variation of average heat-transfer coefficient with engine conductivity for three cylinders having 1/16-inch fin spacing tested with and without disk in nose. Ground run.



(a) Tested in positions 1, 2, and 3.



(b) Tested in positions 4, 5, and 6.

FIGURE 9.—Variation of average heat-transfer coefficient with engine conductivity for three cylinders having 1-inch fin width tested with and without disk in nose. Ground run.

It thus appears that the addition of a disk, if desirable for increasing the pressure available for cooling the baffled part of the cylinder, would not reduce the barrel cooling by more than 20 percent and would slightly increase the cooling on the head.

The effect of fin width is shown in figure 10 for the three fin spacings used. Obviously, there should be an optimum fin width, and it is interesting to note that this optimum is reached within the practicable range. This optimum width undoubtedly depends upon the operating condition. The undesirability of extremely wide fins on the front of a cylinder is clearly demonstrated.

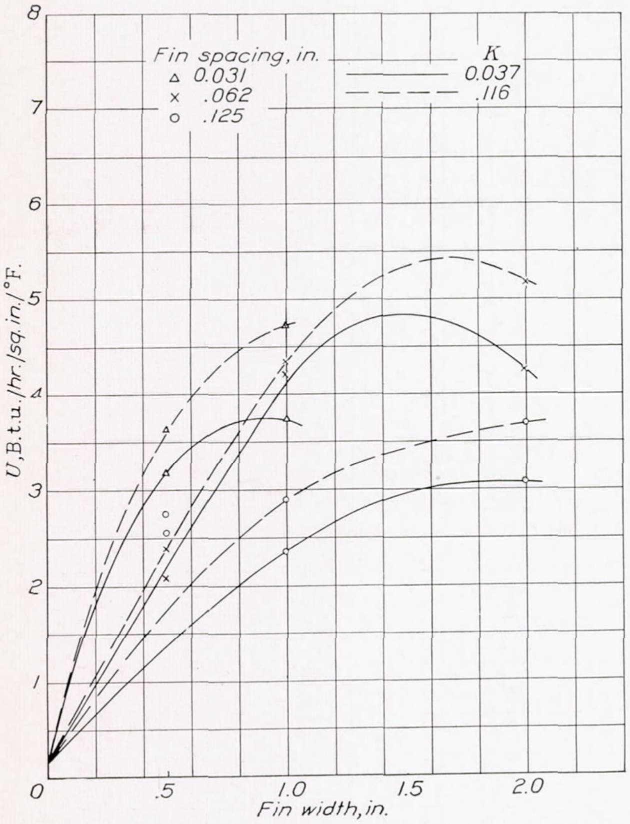


FIGURE 10.—Variation of average heat-transfer coefficient with fin width for three fin spacings at two engine conductivities. All tests in position 3 with wooden cylinders in place. Ground run.

The results from ground-cooling tests indicate that any noticeable change in cooling with changing engine conductivity is in the direction of a slight increase in front cooling with increasing conductivity. Since the supply of heat was insufficient to raise the temperature of the air in the cowling more than a negligible amount, the improvement must be due to increased air flow between the fins. This improvement may, however, be caused by a change in type of flow rather than directly by the flow through the engine. This point needs further study on a set-up better adapted to the investigation.

COOLING IN THE CRUISING CONDITION

All the cooling tests made in the cruising condition were conducted at the same value of P_c, where

$$P_c = \frac{P}{qSV}$$

and P is the power supplied to the propeller shaft.
q, dynamic pressure.
S, propeller disk area.
V, air velocity.

In the cruising condition the propeller is run at various speeds, depending on the air speed; consequently, the swirl induced in the front of the cowling by the propeller varies with the air speed. The tests made at speeds of 40 and 75 miles per hour had propeller speeds of 500 and 895 r. p. m., respectively. These speeds were lower than the propeller speed of 985 r. p. m. at which the ground-cooling tests were made. The tests at 100 miles per hour were made with a propeller speed of 1,145 r. p. m.

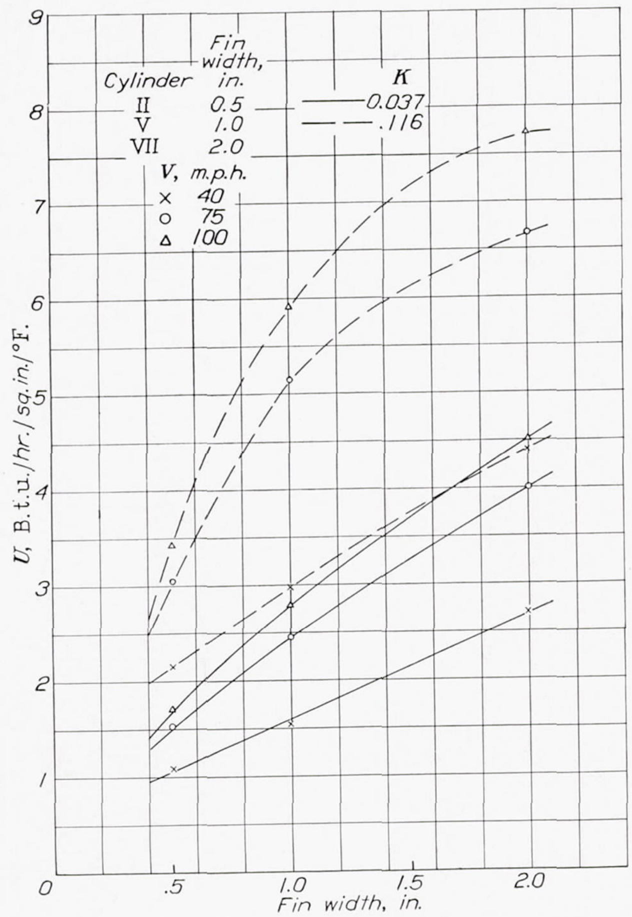
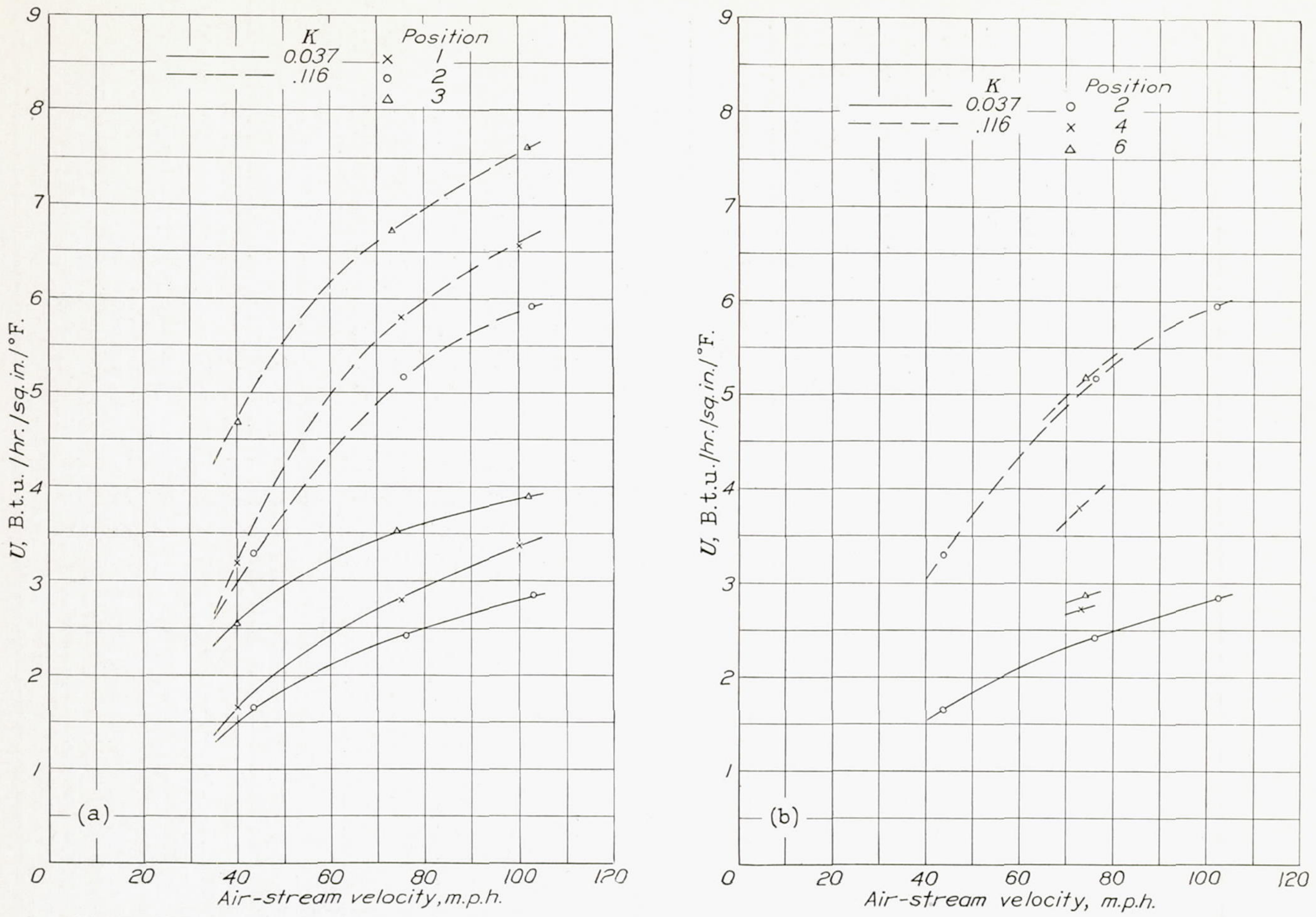


FIGURE 11.—Variation of average heat-transfer coefficient with fin width for three cylinders having 1/16-inch fin spacing, for two engine conductivities and three air-stream velocities. All tests in position 2 with wooden cylinders in place. Cruising condition.

The value of the heat-transfer coefficient increases with increasing values of engine conductivity, air speed, and fin width up to a certain optimum width, for all the cylinders tested. All these effects can be seen in figure 11.



(a) Tested in positions 1, 2, and 3 with wooden cylinders in place.

(b) Tested in positions 2, 4, and 6. No wooden cylinders.

FIGURE 12.—Variation of average heat-transfer coefficient with air-stream velocity for cylinder V for two engine conductivities. Cruising condition.

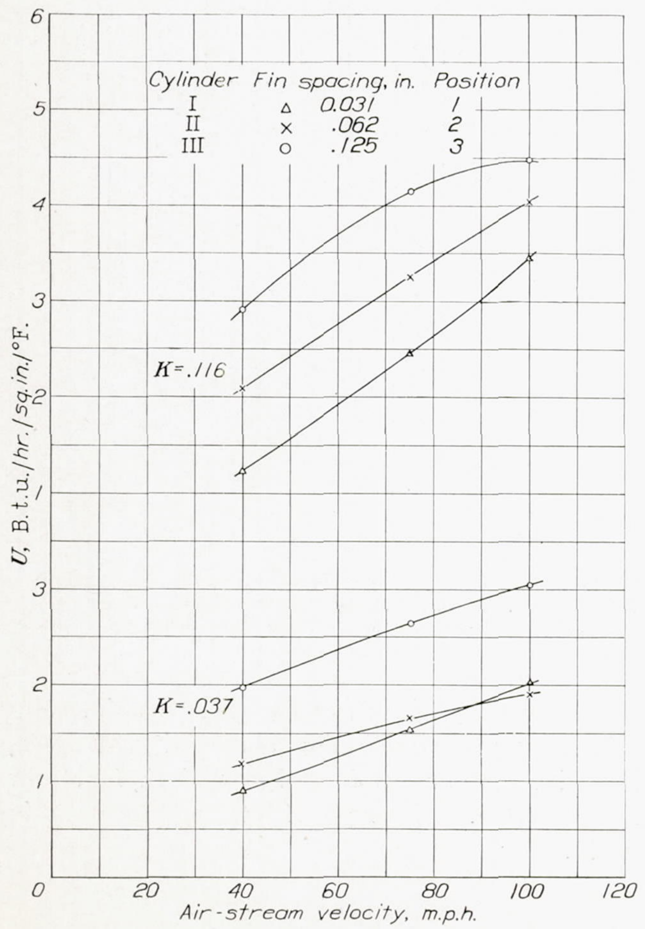


FIGURE 13.—Variation of average heat-transfer coefficient with air-stream velocity for three cylinders having ½-inch fin width in positions 1, 2, and 3 for two engine conductivities. Wooden cylinders in place. Cruising condition.

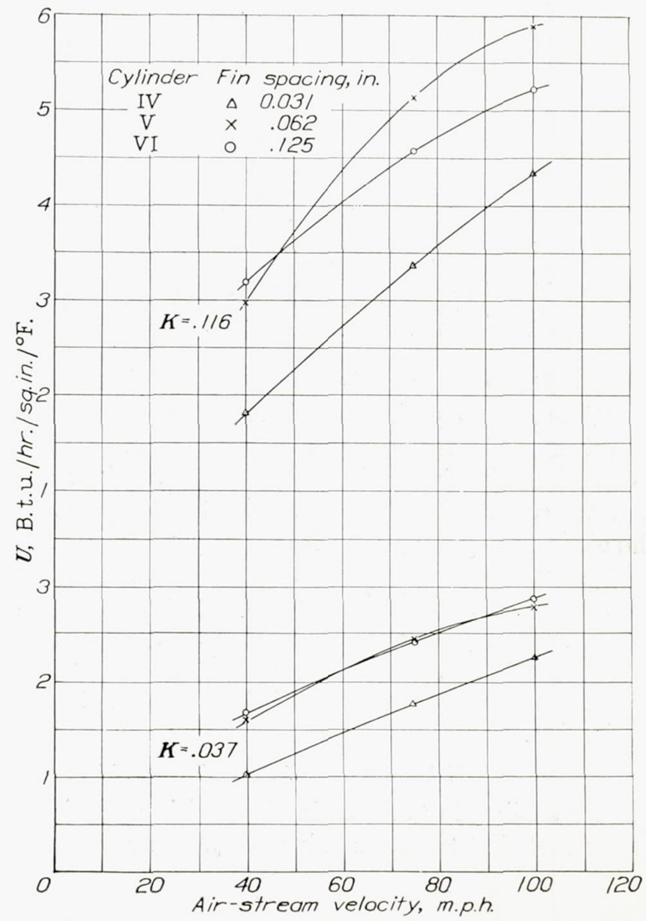


FIGURE 14.—Variation of average heat-transfer coefficient with air-stream velocity for three cylinders having 1-inch fin width in position 2 for two engine conductivities. Wooden cylinders in place. Cruising condition.

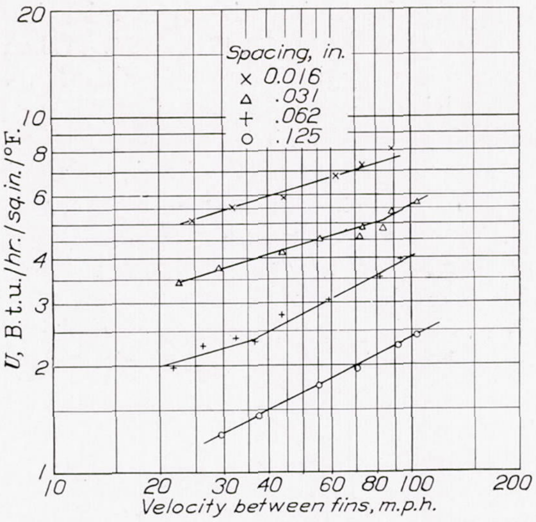
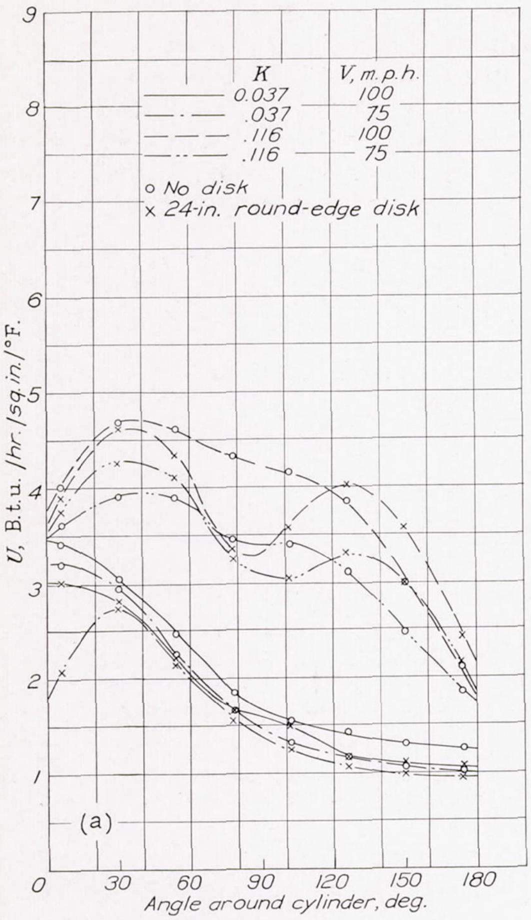
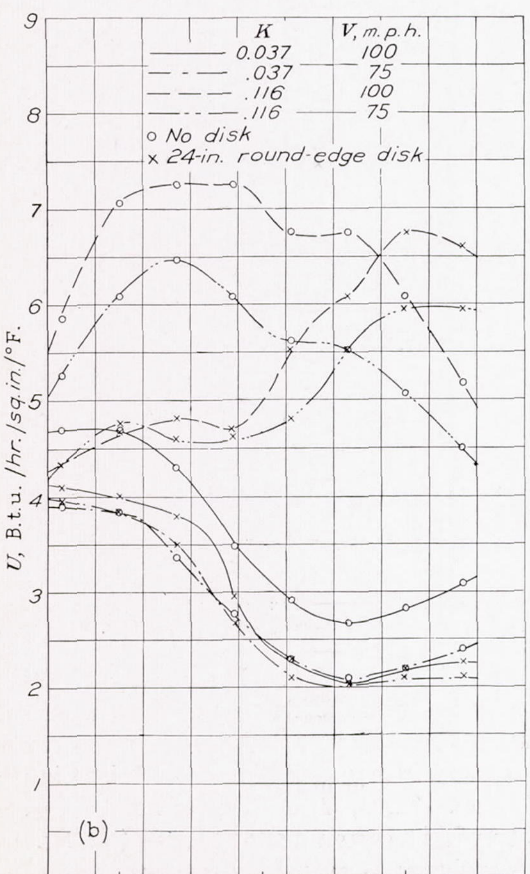


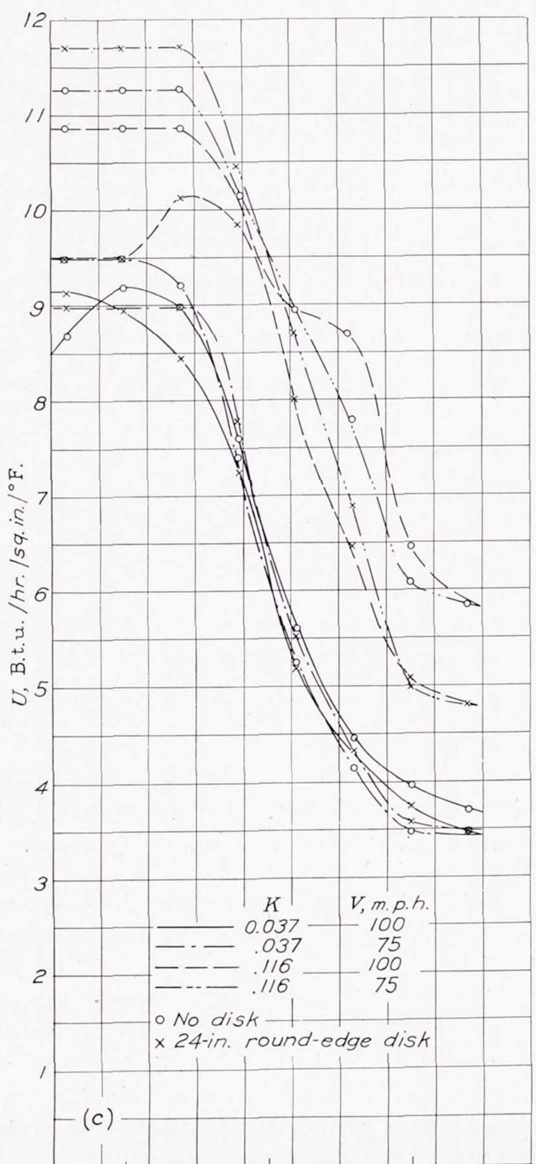
FIGURE 15.—Variation of average heat-transfer coefficient with velocity between the fins on the baffled part of the cylinder.



(a) Cylinder II in position 2.



(b) Cylinder V in position 1.



(c) Cylinder VII in position 3.

FIGURE 16.—Variation of local heat-transfer coefficient with angle around cylinder for three cylinders having $\frac{1}{16}$-inch fin spacing at two engine conductivities and two air-stream velocities, with and without disk in nose. Wooden cylinders in place. Cruising condition.

The variation in cooling with change in air-stream velocity is shown in figures 12, 13, and 14. When these figures are compared with figure 15, which shows heat-transfer coefficients for the rear baffled part of a cylinder as reported in reference 7, it is seen that the cooling on the front of a cylinder compares quite favorably with the cooling on the rear baffled part for the crusing condition.

Figure 16 shows the variation of cooling around a cylinder barrel for cylinders II, V, and VII when the zero angle is on the side of the cylinder facing the propeller swirl. The results show considerably more cooling on the side facing the propeller swirl than on the other side of the cylinder. The large effect of the engine conductivity on cooling is also apparent.

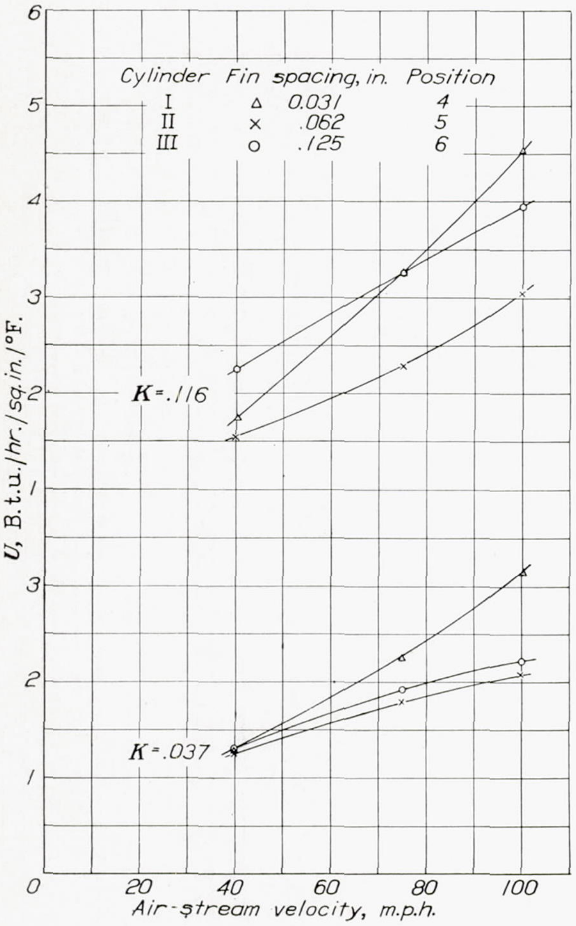


FIGURE 17.—Variation of average heat-transfer coefficient with air-stream velocity for three cylinders having ½-inch fin width in positions 4, 5, and 6, with two engine conductivities. Cruising condition.

The large variation in cooling around a cylinder, especially with wide fins, suggests that either an unsymmetrical baffle could be fitted to even out the temperature distribution or the exhaust valve could be located in the region of good cooling to take advantage of the unequal temperature distribution.

Cooling of cylinders in positions 4, 5, and 6 shows about the same general dependence on air-stream velocity as has already been noted for the other positions. (See fig. 17.)

DISCUSSION

The data presented in figure 6 are rather unexpected; i. e., a spacing of 0.062 inch gave a lower heat-transfer coefficient in the ground condition than either a smaller or a larger spacing with the fins of ½-inch width. In order to check this apparently anomalous behavior, three cylinders were placed in a duct where the air velocity could be varied. The results of this series of tests are presented in figure 18. The small spacings gave a higher coefficient in the high-speed range, and the larger spacings gave a higher coefficient in the low-speed range. Thus, all the curves must cross. Tests run only within certain speed ranges (see fig. 18) will obviously give some surprising results.

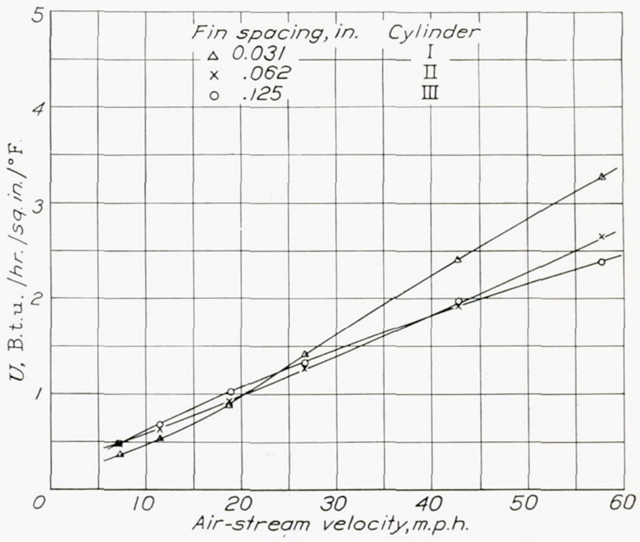


FIGURE 18.—Variation of average heat-transfer coefficient with air stream velocity for three cylinders having ½-inch fin width. Duct tests.

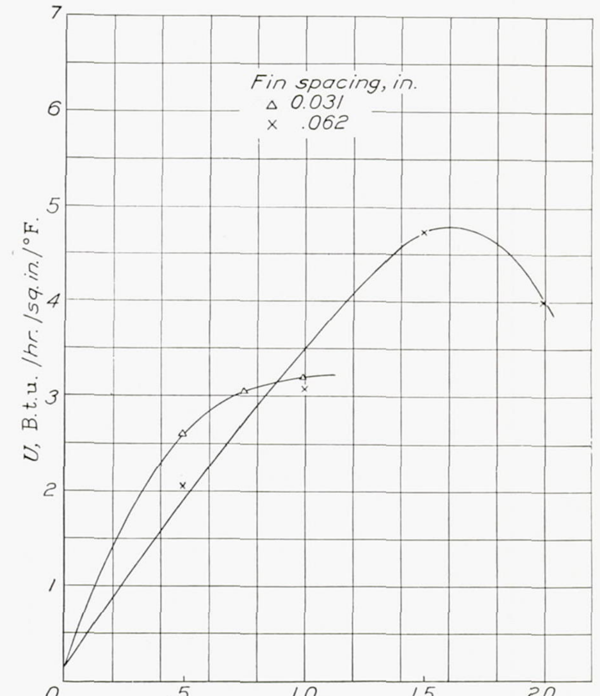


FIGURE 19.—Variation of average heat-transfer coefficient with fin width for two fin spacings at an air-stream velocity of 40 miles per hour. Duct tests.

Figure 10 also presents both interesting and important results, inasmuch as some of the curves indicate an optimum fin width. Although the curves were drawn through the test points in quite an obvious manner, additional points would have been more convincing.

In order to investigate this matter further, several of the model cylinders were tested in a duct. Cylinder VII was cut down to 1½-inch fin width, and cylinder IV was cut down to ¾-inch fin width. These tests (fig. 19) show maximum heat transfer at the same fin widths as the tunnel tests.

Although the duct tests did not exactly reproduce conditions in the front of a cowling, the tests do show that an unbaffled cylinder under certain conditions does have an optimum fin width that falls within the practicable range.

This very important result must be due to the fact that the air flow penetrates to only a limited depth between the fins, as can be seen from figure 18, which shows that the 0.031-inch spacing is too small for its width at low air speeds. Consequently, the air-flow penetration between the fins is restricted and the cooling is poorer than with larger spacings, which allow the air to penetrate deeper. At high air speeds, however, there is sufficient dynamic pressure to cause the air to penetrate all the way to the cylinder wall, even with the 0.031-inch spacing. Full advantage is thus taken of the large fin area associated with narrow spacing, and the fine spacing cools better than either of the coarser spacings.

From the foregoing discussion, it is apparent that an optimum fin width must exist for each combination of fin spacing and air speed. The optimum width is probably the width that allows the air flow to penetrate just to the cylinder wall. For smaller fin widths, the cooling area is reduced. For larger fin widths, the depth of penetration of the air flow is no greater, so that the inner part of the wider fin serves merely as a resistance to heat flow along the fins. The cylinder wall therefore operates at a correspondingly higher temperature while dissipating the same quantity of heat, and the over-all heat-transfer coefficient is lower than with optimum fin width.

The flow on the side of the cylinder facing the propeller swirl or the air stream probably penetrates well to the cylinder wall even in the cylinder with wide fins but undoubtedly leaks out rather rapidly. This probability accounts for the large variation in cooling around the cylinder, which is shown in figure 16(c). Figures 20(a) and 20(b) show a similar variation in cooling around the cylinder for the ground condition. Figure 20(c) shows that a cylinder in position 5 has the best cooling on the side toward the outside of the cowling.

The variation of the heat-transfer coefficient with spacing at various air speeds can probably be explained by the nature of the flow. It appears that the small spacings at low air speeds have too much resistance to air flow to allow the cooling air to penetrate to the cylinder wall. This idea is substantiated by the results in figures 10, 13, and 14, where it can be seen that small spacings are relatively better on narrow fin widths.

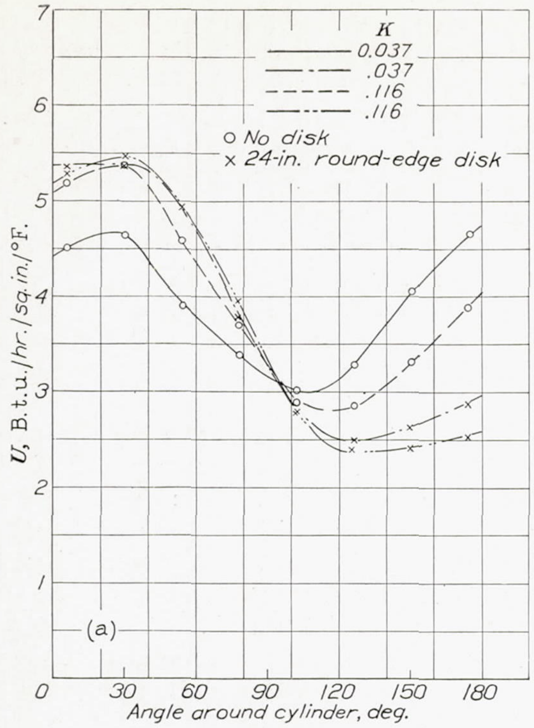
The position of the test cylinder in the front of an open cowling or the orientation of the fins to the propeller swirl has little effect on the cooling of the cylinder. When a disk is added to the front of the cowling, the cooling is somewhat reduced except over parts of the cylinder barrel and head that are exposed to the air stream coming through the slot, where little effect is noticed. The orientation of the fins remains relatively unimportant.

The nature of the air flow that cools the front of cylinders is complex. (See reference 1.) It is composed of at least three types of flow: First, the swirl in the front of the cowling, which is caused by the rotating propeller; second, the fore-and-aft pulsating flow, which is caused by the alternate passage of the propeller blades with the associated regions of high pressure behind them and the open spaces between blades that permit air to escape back through the propeller disk; and third, the straight flow through the cowling, which is caused by high pressure in the front of the cowling as a result of high air speed or propeller speed. The straight type of flow is greatly influenced by engine conductivity.

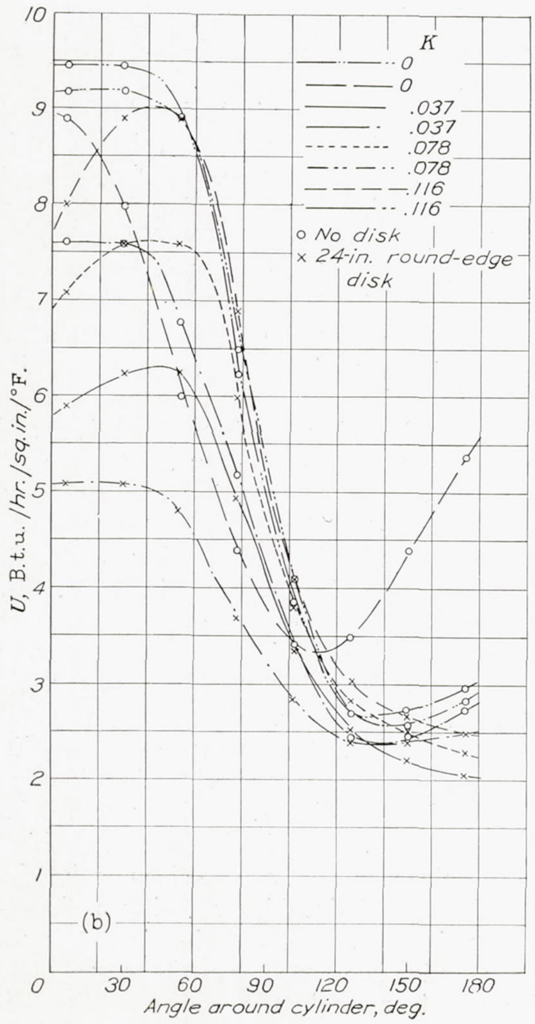
The results presented herein indicate that the heat-transfer coefficient for the ground-cooling condition is roughly the same as for cruising conditions at 60 to 80 miles per hour. Since front cooling in the cruising condition is about the same with or without a propeller operating in front of the engine (see reference 2), it appears that the third type of flow, namely, straight flow through the cowling, controls the configuration of flow and the cooling in the front of the cowling for the cruising condition.

For the ground-cooling condition, there is very little flow straight through the cowling; the first two types of flow, namely, swirl and pulsating flow, must account for the good heat-transfer coefficient obtained. The effect of engine conductivity on cooling is nevertheless important because a large conductivity permits the cooling air to be frequently changed, thus preventing a condition in which air remains in the cowling long enough to warm up by continual contact with the hot cylinders and thus impair the cooling.

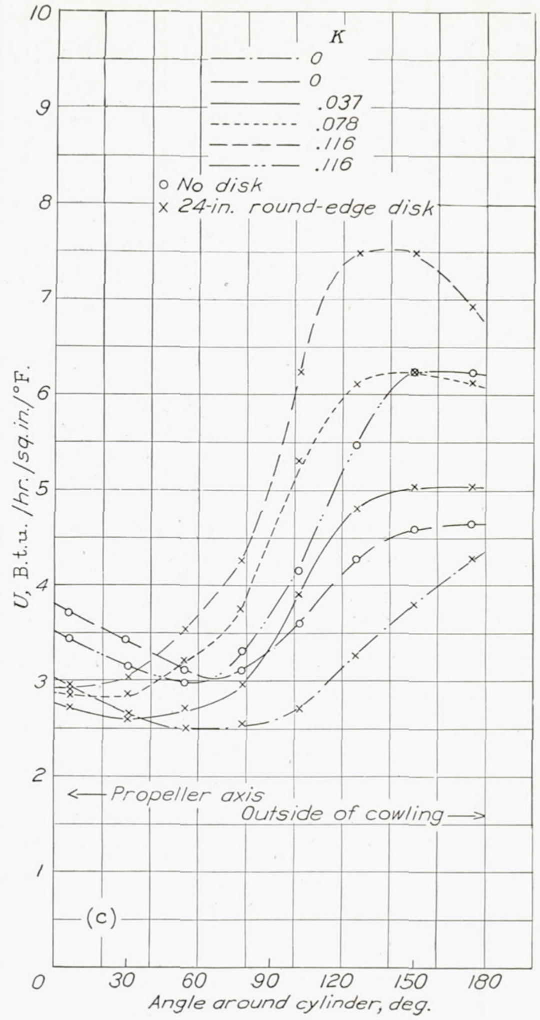
The results of all the tests show that the cooling on the front compares favorably with that in the rear baffled part of the cylinder. This same result was noted in reference 2. The further fact that this front cooling is obtained relatively more cheaply than baffled cooling makes the desirability of using a closed-nose cowling questionable. If fin design is not improved and blower cooling is resorted to as the only alternative, a considerable increase in the cost of cooling will be necessary to give the same cooling; the power increase



(a) Position 1.



(b) Position 2.



(c) Position 5.

FIGURE 20.—Variation of local heat-transfer coefficient with angle around cylinder for cylinder V with 1/16-inch fin spacing and 1-inch fin width for several engine conductivities, with and without disk in nose. Wooden cylinders. Ground condition.

will be roughly proportional to the fifth power of the cooling.

Although the results presented in this report are believed to be representative of the quantitative values of the heat-transfer coefficient to be realized on an actual engine, their chief value lies in the fact that they indicate the comparative importance of various cooling parameters and also the manner in which the variation of each individual parameter affects the cooling of a cylinder.

The results herein presented serve to introduce the problem of front cooling and to give a preliminary answer. The problem should be further studied with a set-up where actual engine cylinders in a cowling can be tested under operating conditions simulating ground, climb, and cruising conditions. In this manner, the elative cooling of the front and the rear of the cylinder, as well as the effect of fin dimensions, fin arrangement, and baffle arrangement on cooling, can be determined. This information is especially important because recent cooling determinations (results unpublished) show that the power cost for this cooling is lower by far than the power cost of any other arrangement, in addition to the advantage of the extreme simplicity of the cooling system.

CONCLUSIONS

The cooling in the front of a cowling was:

1. Not greatly dependent on the position or the orientation of the cylinder within the cowling for usual engine conductivities.
2. Improved by an increase in engine conductivity in the cruising condition.
3. A function of the propeller speed, improving as the speed increased.
4. A function of fin width, the optimum fin width falling within the usable range.
5. Improved by narrower spacing to the point where the air-flow resistance was too high.
6. Increased by an increase in air speed.
7. Slightly decreased by the use of a stationary disk behind the propeller.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *April 5, 1939.*

REFERENCES

1. Stickle, George W., and Joyner, Upshur T.: The Pressure Available for Ground Cooling in Front of the Cowling of Air-Cooled Airplane Engines. T. N. No. 673, N. A. C. A., 1938.

2. Theodorsen, Theodore, Brevoort, M. J., and Stickle, George W.: Full-Scale Tests of N. A. C. A. Cowlings. T. R. No. 592, N. A. C. A., 1937.

3. Brevoort, M. J., Stickle, George W., and Ellerbrock, Herman H., Jr.: Cooling Tests of a Single-Row Radial Engine with Several N. A. C. A. Cowlings. T. R. No. 596, N. A. C. A., 1937.

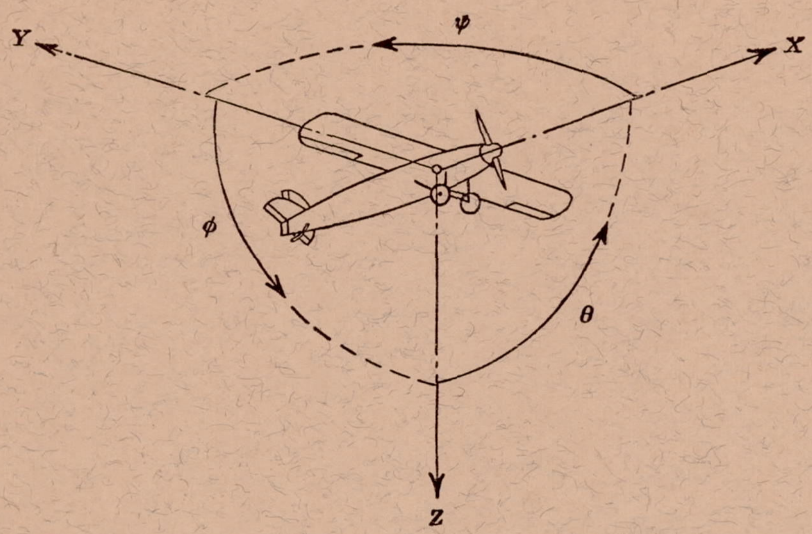
4. Theodorsen, Theodore, Brevoort, M. J., and Stickle, George W.: Cooling of Airplane Engines at Low Air Speeds. T. R. No. 593, N. A. C. A., 1937.

5. Brevoort, Maurice J.: Energy Loss, Velocity Distribution, and Temperature Distribution for a Baffled Cylinder Model. T. N. No. 620, N. A. C. A., 1937.

6. Brevoort, Maurice J.: The Effect of Air-Passage Length on the Optimum Fin Spacing for Maximum Cooling. T. N. No. 649, N. A. C. A., 1938.

7. Brevoort, M. J.: Principles Involved in the Cooling of a Finned and Baffled Cylinder. T. N. No. 655, N. A. C. A., 1938.

U. S. GOVERNMENT PRINTING OFFICE: 1939



Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$

C_s, Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{P n^2}}$

η, Efficiency

n, Revolutions per second, r.p.s.

Φ, Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp.=76.04 kg-m/s=550 ft-lb./sec.

1 metric horsepower=1.0132 hp.

1 m.p.h.=0.4470 m.p.s.

1 m.p.s.=2.2369 m.p.h.

1 lb.=0.4536 kg.

1 kg=2.2046 lb.

1 mi.=1,609.35 m=5,280 ft.

1 m=3.2808 ft.