NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 662

DESIGN OF N. A. C. A. COWLINGS FOR RADIAL AIR-COOLED ENGINES

By GEORGE W. STICKLE

1939

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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/s^2 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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By GEORGE W. STICKLE
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DESIGN OF N. A. C. A. COWLINGS FOR RADIAL AIR-COOLED ENGINES

By George W. Stickle

SUMMARY

The information on the propeller-cowling-nacelle combinations, presented in Technical Reports Nos. 592, 593, and 596 and in Technical Note No. 620, is applied to the practical design of N. A. C. A. cowlings. The main emphasis is placed on the method of obtaining the dimensions of the cowling; consequently, the physical functioning of each part of the cowling is treated very briefly. A practical method of designing cowlings and some examples are presented.

INTRODUCTION

When the radial air-cooled engine was first introduced, the engine cylinders were cooled by exposing them to the air stream. In 1929 the N. A. C. A. reported the results of some tests (references 1 and 2) in which the cylinders were enclosed by a sheet-metal ring or cowling, which became known as the "N. A. C. A. cowling." This cowling reduced the drag of the radial engine to less than one-fifth its original value and gave sufficient cooling for flight operation. In order to improve the cooling obtainable with this cowling, deflectors or baffles were used to guide the air close to the cylinders. With the combination of baffles and cowling, a large gain over the exposed engine in both cooling and drag was realized. At this stage of the development, cut-and-try methods were largely used in cowling design. Often a supposed improvement in design resulted in a decrease in performance and cooling.

A very comprehensive investigation of the cowling and cooling problem was made by the N. A. C. A. in 1935. The general purpose of this investigation was to furnish information on the physical functioning of the propeller-nacelle-cowling unit under various conditions of flight operation. The information obtained (references 3, 4, 5, and 6) embodies the detailed principles of operation. If a complete understanding of the cowling and cooling problem is obtained, the problem of the dimensions of the installation is a very simple one. Such an understanding may be obtained from the fundamental principles of cowling operation presented in references 3 to 6. Inasmuch as the designer of an airplane has neither the time nor the opportunity to acquire a detailed knowledge of every part of the airplane, he wants a simple method of obtaining the optimum cowling dimensions and, perhaps, some of the more important reasons for selecting these dimensions. It is the purpose of this report to present such a method and to illustrate the method with a discussion of practical examples.

The design of a cowling may be divided into two parts: (1) The nose section, and (2) the exit slot. Each part may be considered separately because the functions of each part are separate and distinct. The nose section, or leading edge of the cowling, must have an opening in the center to allow cooling air to enter the engine compartment and be of such shape that it will smoothly divide the air entering the cowling from the air going around the outside. The exit slot returns the cooling air to the main air stream and its area controls the amount of air flowing around the engine.

The complement of a good cowling design is a good baffle design. A brief discussion of baffle design and dimensions will therefore be given to complete the analysis of the design problem.

DESIGN DISCUSSION

THE NOSE SECTION

Figure 1 (from reference 3) is a portion of a motion-picture film of smoke flowing over the nose of an N. A. C. A. cowling. Three significant facts can be discerned from this figure: (1) The direction of the air stream immediately in front of the cowling is almost radial; (2) the percentage of the main air stream that enters the cowling is very small, as can be observed by noting the distance between the nozzle producing the smoke and a straight line drawn through the engine propeller-shaft axis; and (3) the velocity inside the nose of the cowling is low, shown by the way the smoke accumulates in this region. These photographs are for the condition of propeller off. It has been shown (reference 3), however, that the same conditions exist with propeller on.

In terms of design conditions, these conditions indicate that: (1) The contour of the nose shape must meet the local radial air flow and have a large enough radius

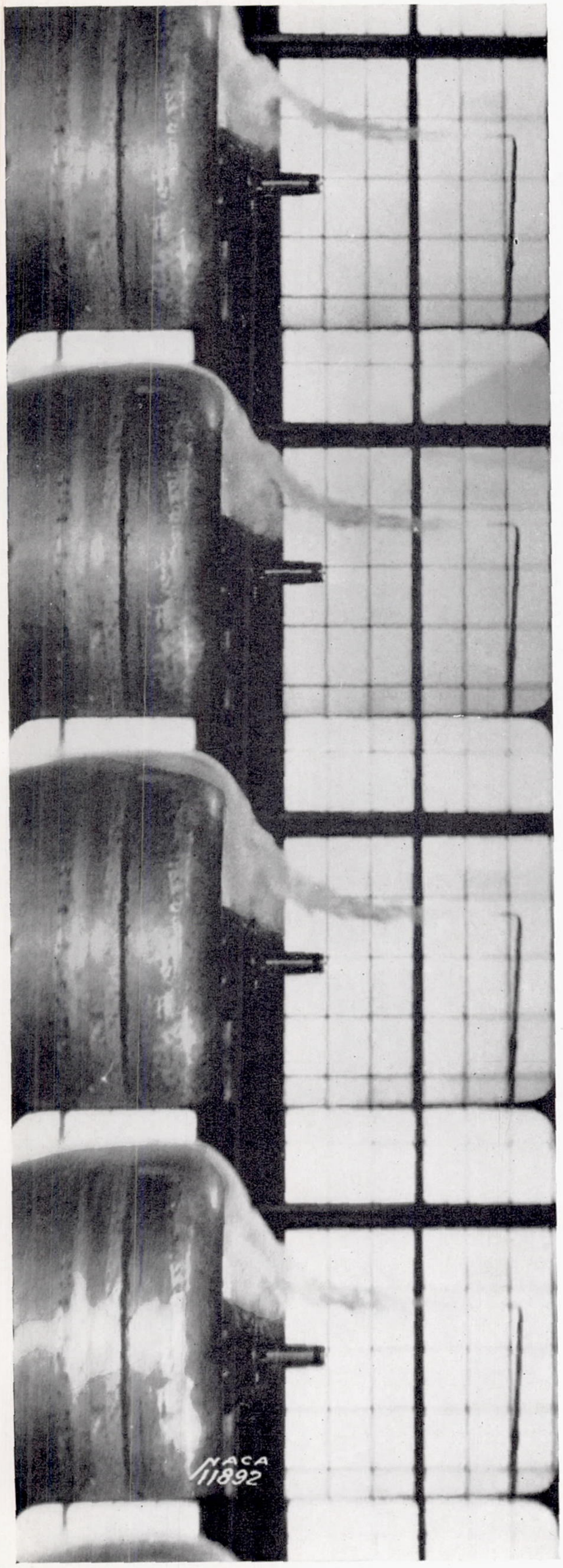


FIGURE 1.—Smoke flow over the nose of an N. A. C. A. cowling.

of curvature to allow the flow to follow the shape smoothly and efficiently until it is flowing parallel to the main air stream; and (2) the shape of the inside of the cowling or of anything located inside the nose of the cowling is unimportant, for the velocity is low in this region. The shape of the inside of the nose being unimportant, the only necessary dimensions for the design of the nose section are those of the outside contour. Well-designed nose sections must therefore have a change in angular direction of approximately 90°. The curvature is determined by the length in which this angular change takes place and is governed by the distance between the engine rocker boxes and the trailing edge of the propeller. The two designs given in figure 2 are the best contours for their particular dimensions and cover the normal variation of length as encountered in practice. Either design may be used with almost identical results at speeds below 350 miles per hour. Above that speed, nose 1 is recommended, as the maximum local velocity produced by this cowling is less than that for nose 2 and, if the local velocities exceed the velocity of sound, the drag of the cowling will be multiplied many times.

THE EXIT SLOT

The important factors in the design of an efficient exit slot are the shape and the area of the exit passage. The shape determines the efficiency of the slot; and the area, the pressure available for cooling the engine. The exit passage should be smooth, with a gradually diminishing area so that the cooling air will have a maximum speed at the exit, and should be of such shape as to give this air a direction parallel to the direction of the outside flow. For maximum efficiency in mixing the two air streams, the streamlines of the outside flow should be straight as they pass the exit passage. An example of a good exit passage is given in figure 2.

The conductivity of the exit slot may be represented by the ratio of its area to the frontal area of the engine.

$$K_2=\frac{\text{area of exit slot}}{F}$$

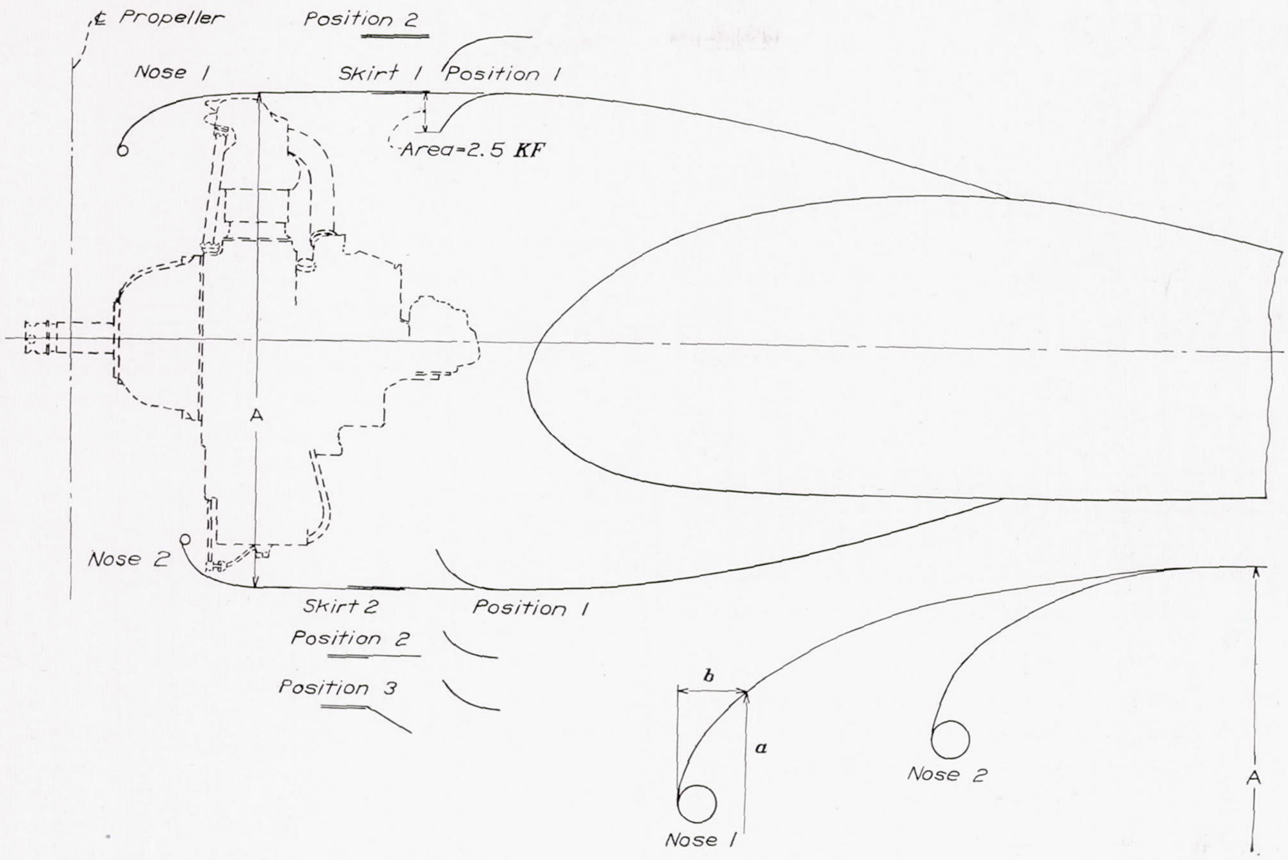
In like manner the conductivity of the engine may be defined as the ratio of the "equivalent leak area" and the frontal area of the engine.

$$K=\frac{Q}{FV\sqrt{\frac{\Delta p}{q}}}=\frac{\text{equivalent leak area}}{F}$$

where

$$\frac{Q}{V\sqrt{\frac{\Delta p}{q}}}=\frac{Q}{\sqrt{\frac{2\Delta p}{\rho}}}=\text{equivalent leak area}$$

Q, quantity of air flowing through the engine.



Station		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	b/A	0	.01	.02	.04	.06	.08	.10	.13	.15	.16	.19	.22	.25	.28
Nose 1	a/A	.759	.821	.847	.883	.909	.930	.947	.965	.974	.978	.987	.994	.998	1.00
Nose 2	a/A	.824	.885	.911	.945	.967	.982	.990	.993	1.00	----	----	----	----	----

FIGURE 2.—Diagrammatic sketch of N. A. C. A. cowlings.

V, velocity of the air stream.
q, dynamic pressure of the air stream.
Δp, the pressure drop across the engine baffles.
F, the frontal area of the engine.
ρ, density of the air.

The equivalent leak area may be experimentally determined by measurement of the volume of air flowing through the engine and the pressure drop across the baffles. If these measurements cannot be made, an approximate determination of the equivalent leak area can be substituted. The equivalent leak area is equal to the geometric leak area multiplied by an orifice coefficient ranging from 0.65 for a poorly designed baffle exit to 0.85 for a good exit. (See reference 5.)

From reference 3 the use of the total available pressure across the cowling is governed by these two quantities in accordance with the following formula:

$$\frac{\Delta P}{q}=\left(\frac{Q}{FV}\right)^2\left[\frac{1}{K^2}+\frac{1}{K_2^2}\right]$$

where ΔP is the total available pressure across the cowling.

From reference 3

$$\frac{\Delta p}{q}=\left(\frac{Q}{KFV}\right)^2=\frac{1}{K^2}\left(\frac{Q}{FV}\right)^2$$

By substitution

$$\frac{\Delta P}{q}=K^2\frac{\Delta p}{q}\left[\frac{1}{K^2}+\frac{1}{K_2^2}\right]=\frac{\Delta p}{q}\left[1+\left(\frac{K}{K_2}\right)^2\right]$$

For the usual type of cowling, $\Delta P/q$ is nearly equal to unity. It is therefore possible to determine the $\Delta p/q$ available across the engine from a knowledge of the ratio K/K_2.

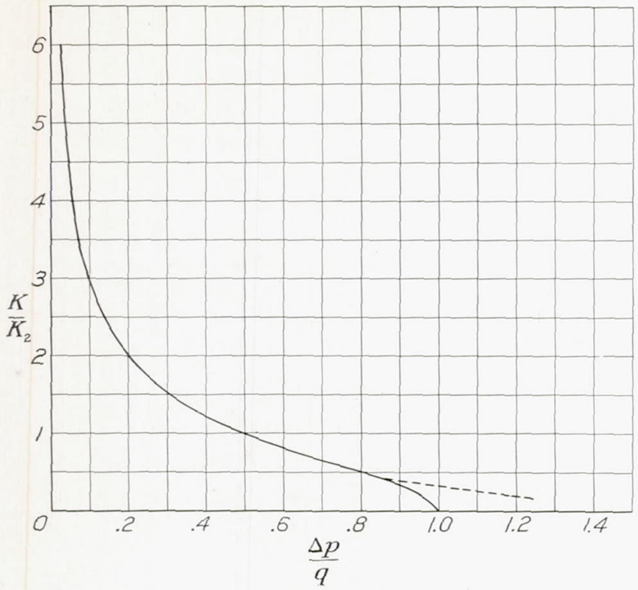


FIGURE 3.—Relationship of $\Delta p/q$ and K/K_2 for a slot design as shown in figure 2.

A plot showing the relationship of these quantities is given in figure 3. The solid line is for normal cowlings that have an available $\Delta P/q$ of unity, and the dotted part is an extrapolation to an experimental point obtained with cowling flaps.

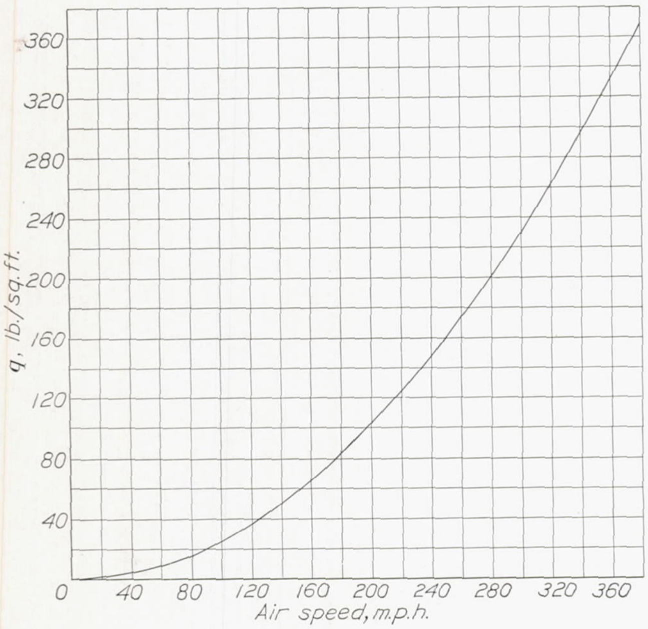


FIGURE 4.—Relationship of air speed and q for standard conditions.

Figure 4 is a plot of dynamic pressure q against air speed. It has been shown from tests that a fixed exit slot will give a constant $\Delta p/q$ regardless of air speed.

Figure 5 is a plot of the power required for standard air conditions for cooling an engine of 52-inch diameter for which $K=0.05$. The plot represents two types of exit slot that will furnish a Δp equal to 20 pounds per square foot at a climbing speed of 100 miles per hour. The fixed-slot design will give this same $\Delta p/q$, which is equal to 0.78, at the higher speeds and consequently will overcool the engine at a large expenditure of unnecessary power. The controllable-slot design will furnish the same Δp regardless of speed and the enormous saving in power can be noted from the curves.

In order to maintain a fixed pressure drop across the baffles, it is necessary to have an exit slot of variable area. Two methods of varying this area are: (1) By moving the skirt forward and backward, as skirt 1 (fig. 2); and (2) by the use of cowl flaps that open outward, as skirt 2, position 3. Method (1) has the distinct advantage of maintaining a good slot design by a variation of area. A maximum $\Delta p/q=1.0$ is available, which will furnish sufficient cooling for most commercial designs and also for many military designs. If cowl flaps

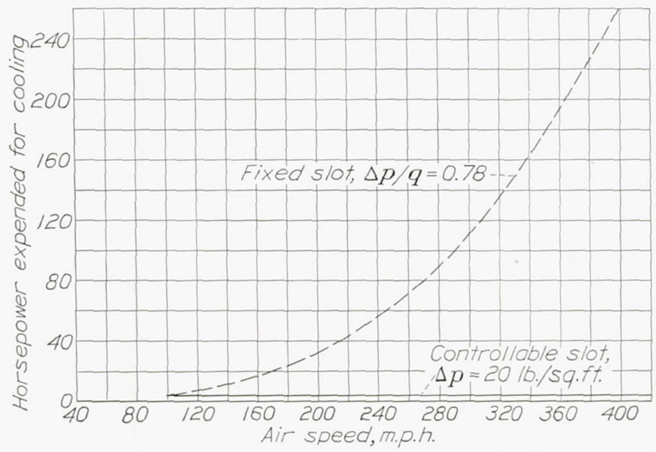


FIGURE 5.—Comparison of power expended for cooling with fixed-slot and controllable-slot designs.

are used, as shown in figure 2, the slot efficiency is not so high for large areas but there is about a 30-percent increase in the available pressure drop for cooling for the low-speed climbing condition. If cooling on the ground, or on the water, is a difficult problem, a combination of the two methods (skirt 2) will give the best results.

COWLING DRAG

The cost of cooling an engine was evaluated by plotting test data, taken from reference 3, to show the cooling drag associated with the flow of air through the cowling, $\Delta C_D=C_D-C_{D_0}$, where C_{D_0} is the drag coefficient of a cowling that has a closed skirt smoothly faired into the nacelle, or the C_D obtained with zero cooling air.

Figure 6 is a plot of $\Delta p/q$ against ΔC_D taken from a cross plot of the results presented in reference 3. It covers all the normal conductivities encountered with baffled engines and shows the increase in drag due to pumping the air through the engine. This value of

ΔC_D should remain nearly constant for any well-designed exit slot, regardless of the interference drag of wing or fuselage near the nacelle. The power required for cooling may be determined by the use of figures 4 and 6 and the equation

$$\text{Power}=\Delta C_D qFV$$

$$=\Delta C_D \frac{\rho}{2} FV^3$$

or

$$\text{hp.}=\Delta C_D \frac{\rho}{2} \frac{FV^3}{550}$$

The total drag of a nacelle alone is subject to interference corrections, determined by the location of the engine on the airplane. If the cowling is mounted on the wing of an airplane, the interference drag can be computed from references 7 and 8, which give data for a ratio of wing thickness to nacelle diameter of 60 percent. As the wing thickness becomes more nearly equal to the nacelle diameter, as is the case for many modern airplanes, the interference correction will become larger, reducing the nacelle drag even more than is indicated in references 7 and 8.

Mounting an N. A. C. A. cowling on the front of a fuselage is similar to mounting it on the front of a nacelle. If the drag of the nacelle or fuselage with a streamline nose shape is known, the additional drag caused by adding a cowling can be computed from test data. Reference 3 gives $C_D=0.0861$ for the nacelle with a streamline nose and 0.1193 for the same nacelle with an N. A. C. A. cowling and zero cooling air. The difference between these two values, $C_D=0.0332$, is the C_D added by the cowling. As the only change is that of the nose shape, the same increment of drag can be expected when a cowling is placed on the front of a fuselage. It should be noted that the value is

$$C_D=\frac{D}{qF}$$

where F is the frontal area of the engine.

The performance for the condition without the propeller has thus far been discussed. The tests of references 3 to 6 were made with propellers and the net efficiencies of the combinations were determined. It has been shown (reference 3) that the best cowling without a propeller is also best with a propeller.

Mounting the nacelle in front of a wing introduces interference effects that are of the order of half the drag of the well-designed nacelle alone. Tests have been made of many combinations of cowlings, propellers, nacelles, and wings (references 7 and 8) to determine the best location of the nacelle with reference to the wing. Although the best location determined in those tests probably remains the same, the magnitude of the interference is changed by the relative sizes of the nacelle and the wing and by the drag of the nacelle. Interference tests are necessary for wings of a thickness equal to or greater than the nacelle diameter. The basic nacelle without cooling air should be tested so that a change in the amount of cooling air, due to changing the location of the nacelle, would not affect the results. Such tests are being planned; they should help evaluate the performance of the units of cowlings, propellers, nacelles, and wings that are encountered in modern airplanes.

It should be pointed out that the interference does not affect the design of the best cowling for a given engine. The cooling drag can easily be computed and will not seriously affect the interference drag.

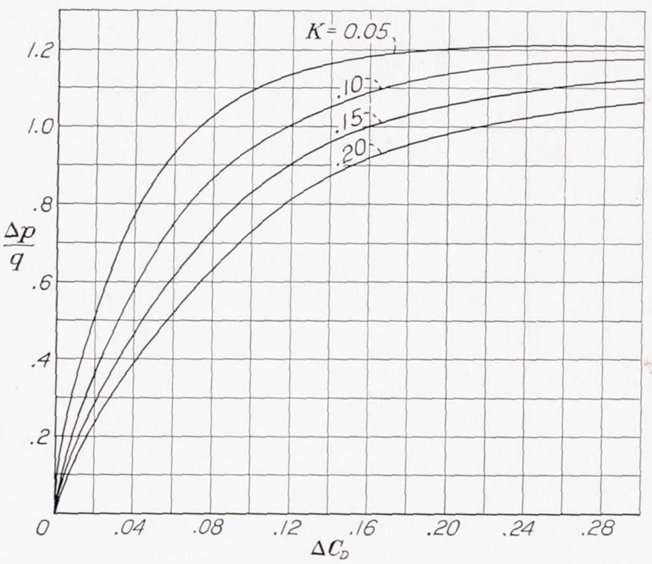


FIGURE 6.—Curves of $\Delta p/q$ against ΔC_D for the most useful conductivities of baffled engines.

COMMON MISCONCEPTIONS REGARDING EXIT SLOTS

Thus far, the discussion has dealt with the "ideal" exit slot. Poorly designed exit slots will now be discussed and some suggestions for improvement will be given.

The practice of placing the exhaust collector ring at the exit of the slot (fig. 7 (a)) greatly increases the drag and has little to recommend it as a means of keeping the exhaust heat from the accessory compartment. The two exit slots illustrated would provide equal cooling pressure for the engine but the drag of the poor shape would be much higher than that of the improved design. The amount of exhaust heat reaching the accessory compartment would be almost equal in the two cases, because the radiated heat from the exhaust ring is constant and the induced flow past the ring is sufficient in both cases to keep any heat from entering the accessory compartment by conduction.

The practice of keeping the frontal area of the engine cowling small when the cowling is placed on the front of a large fuselage (fig. 7 (b)) is very detrimental to the available cooling pressure and does not decrease the drag. If the slot is located in front of a large obstruction, the static pressure at the slot will be high and very poor cooling will result. This fact is especially true at low air speeds and at large propeller thrust.

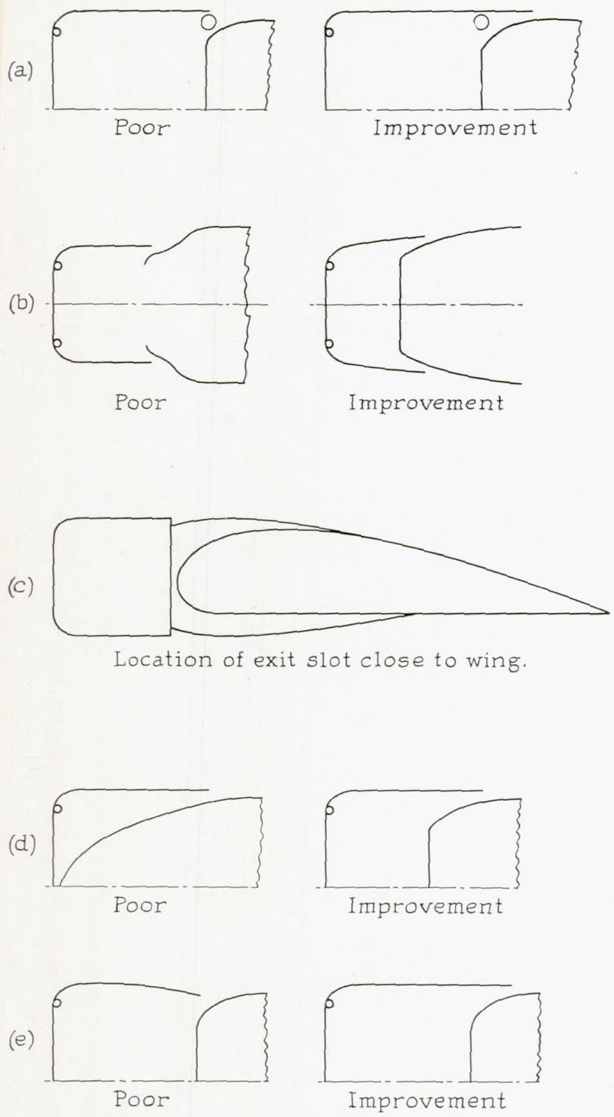


FIGURE 7.—Examples of exit-slot designs sometimes seen in practice.

For one airplane, the ground cooling pressure was zero with the slot located in a much smaller depression than that shown. In many installations, only part of the slot is located in front of an obstruction. This condition may give rise to a reversal of flow in the slot and produce a circulation within the slot itself. The remedy in this case would be to close the slot in the high-pressure region and to provide the required area in the unobstructed region. Flaps are sometimes put on the cowling skirt to improve the cooling for this condition. Their effectiveness is greatly reduced if not eliminated, however, owing to the low velocity caused by the obstruction.

If the nacelle is mounted in front of a wing (fig. 7 (c)), the flow over the wing will affect the static pressure of the main air stream at the exit slot. If it is located close to the leading edge of the wing, the pressure distribution over the wing will largely determine the static pressure. For example, on the top of the nacelle and wing the static pressure will be negative, immediately in front of the leading edge the static pressure will be nearly equal to q, and below the wing the static pressure will be positive. As the nacelle is moved farther forward, this effect will be diminished. In the design of the exit slot, these factors should be considered. If a part of the slot is opened in a region of high positive pressure and part in a region of low pressures, a circulation of air occurs within the slot itself. The air enters the slot in the high-pressure region and is expelled in the low-pressure region, causing a needless loss of energy and a reduction in the ability of the slot to induce flow through the cowling.

The long inner cowling that extends through the cylinders to the front of the cowling (fig. 7 (d)) is a needless weight and complication and has a detrimental effect on the cooling of the crankcase. The improved shape shown in figure 7 (d) is equally effective and is much simpler to construct. There is no advantage in extending the inner cowling beyond the plane in which the cross-sectional area of the exit passage is three times the area of the exit slot.

Certain designers believe that the most efficient skirt design is one having a smaller diameter at the exit than the maximum cowling diameter (fig. 7 (e)). This idea arose from the practice of comparing the performance of exit slots without considering the available cooling pressure. Test results (reference 3) show that this conception is wrong and that the best skirt design is one for which the streamlines of the main air flow are straight.

Many misconceptions with regard to skirt and slot design prevail because tests have not been compared on the basis of equal cooling. The exit passage having a smooth contour that speeds up the air to a maximum at the exit and gives it a direction parallel to the main air stream is the most efficient. Skirt 1 (fig. 2) will give maximum efficiency at any cooling with a sufficient range of cooling for most airplane designs. Skirt 2 provides maximum efficiency for conditions where efficiency is the controlling design factor and maximum cooling for the condition of low-speed operation where maximum cooling is the controlling design factor.

BAFFLE DESIGN

In the design of a cowling, a certain pressure drop across the cylinders is made available. Baffles should be designed to make the best use of this available pressure drop for cooling. The best baffles cause the greatest amount of heat to be carried away from the cylinder fins and maintain an even temperature distribution.

The correct baffles and the Δp required for adequate cooling at any power may be determined for any engine. All other engines of the same specifications will require the same pressure drop and baffles. Thus the designing of baffles is a problem for the engine manufacturer and the solution should be furnished as part of the standard engine data. The front of the engine cylinder is cooled in flight by large-scale turbulence; therefore it is important that the determination of the required Δp be made either in flight tests or in tests simulating flight conditions. If this turbulence is not present in the test determination of Δp, the pressure drop required for adequate cooling will be too large.

The front part of the engine cylinder should be left entirely free of baffles to allow this turbulent air to come in contact with the cylinder fins. The amount of the cylinder that can be satisfactorily cooled by this low-velocity, highly turbulent air is a little uncertain. It is known that at least the front half of the cylinder should be left open to this turbulent cooling air; perhaps even more of the cylinder can be so cooled.

In the design of the best baffle to cool the rear half of the cylinder, the work reported in reference 5 is very helpful. The preliminary baffles designed for a new engine should be tightly fitting; they should have a rear opening approximately 1.4 times the free area between the fins, a bend at the exit having a radius equal to the fin depth, and as long an expanding duct as is practicable for the given installation. The included angle between the sides of the expansion duct should not be more than 20°. (See fig. 8.) The temperature distribution around the cylinder or over the head should be determined for this baffle. If this distribution is not satisfactory, it may be improved by a suitable alteration in the baffle. For example, if the tightly fitting baffle gives a temperature too low at the baffle entrance and too high at the rear of the cylinder, the baffle may be moved away from the fins at the front and a higher velocity to cool the rear of the cylinder will result. (See reference 5.)

The same principles apply to the baffling of a double-row radial engine. The rear bank of cylinders is cooled in the same manner as the front bank. The front of the cylinders should be left as open as possible to allow the turbulent cooling on the front to have free access to the cylinder fins. An example of a good baffle design for a

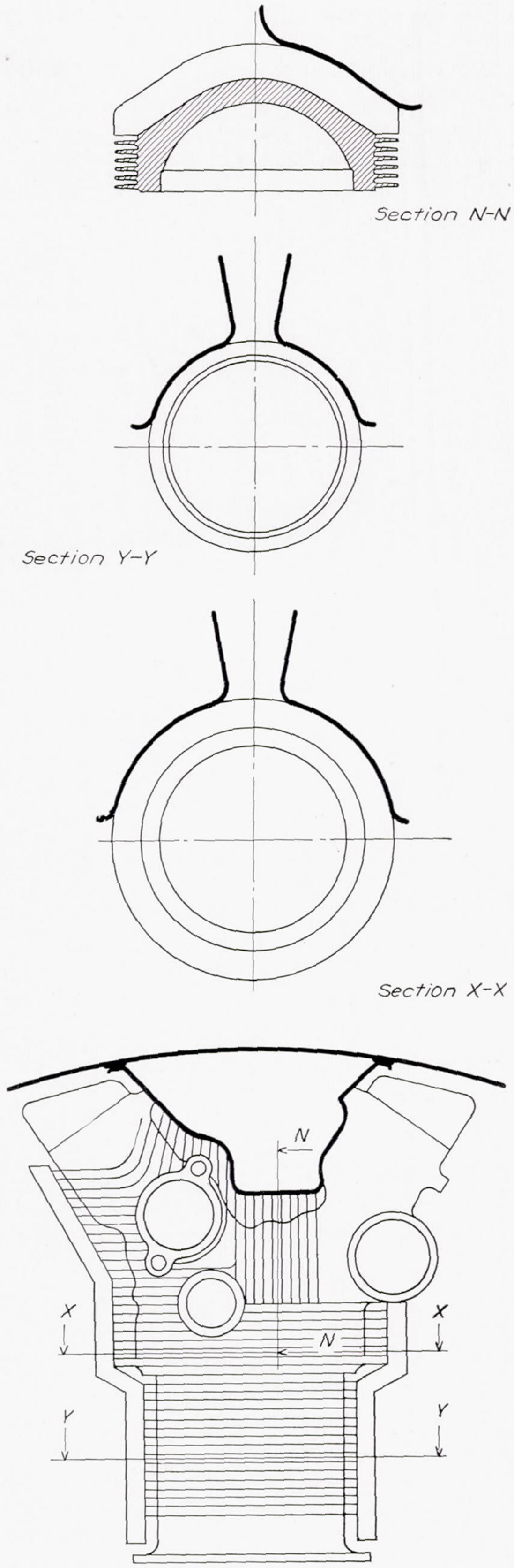


FIGURE 8.—Typical baffle design for a cylinder of a radial engine.

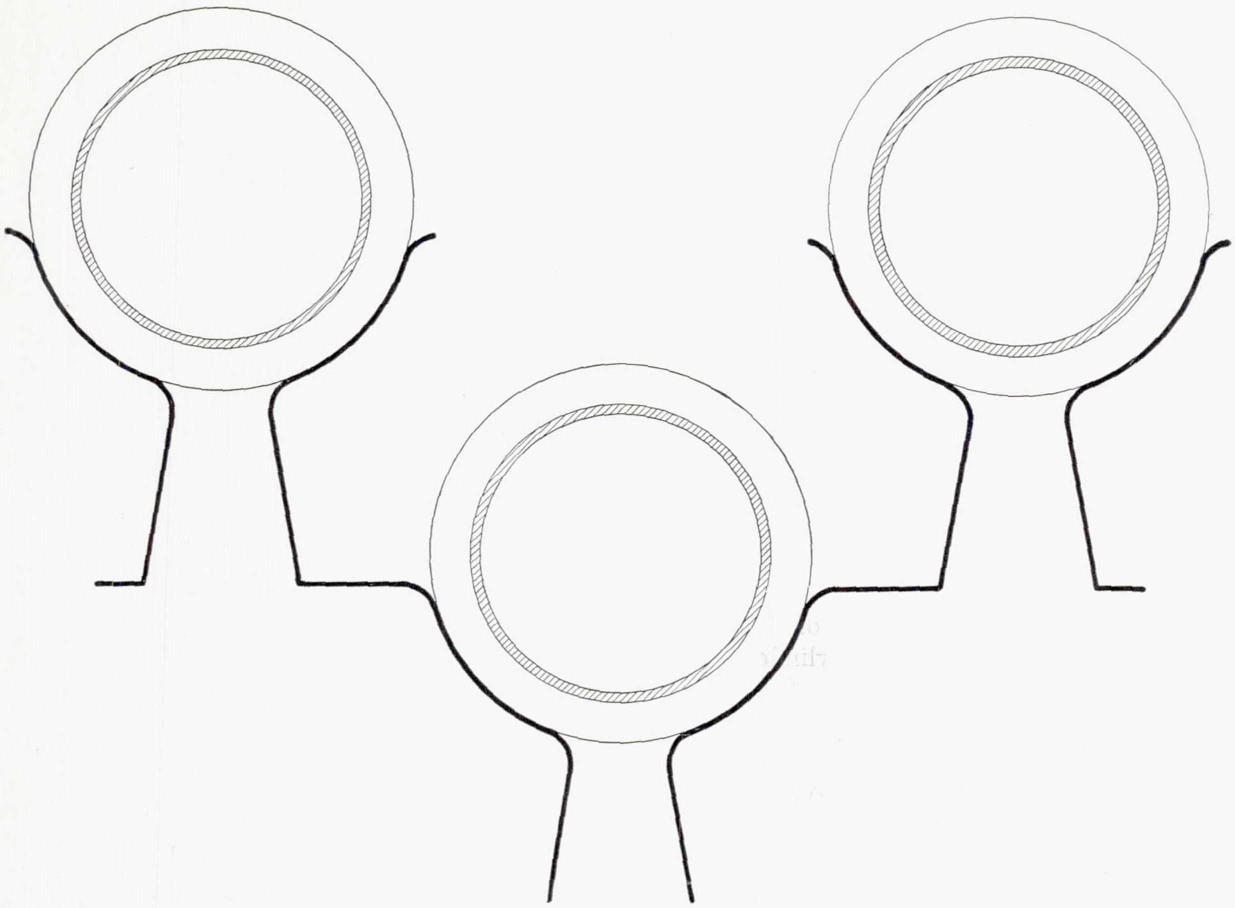


FIGURE 9.—Baffle design for a double-row radial engine.

double-row radial engine is given in figure 9. The straight portion between the exit of the front baffle and the entrance to the rear baffle can be varied in length to accommodate the change in distance between the cylinders as the radius is varied.

The application of the design discussion will be illustrated by two examples.

EXAMPLE I

DESIGN COMPUTATIONS

Airplane type: Commercial land monoplane.
Number of engines: 2.
Cruising speed of airplane: 200 m. p. h.
Climbing speed of airplane: 170 m. p. h.
Engine diameter: 51⅞ in.
Engine power: 550 hp. at 2,200 r. p. m.
Number of cylinders: 9.
Type of baffle: Commercial.
Propeller drive: Geared.
Maximum wing thickness at engine location: 30 in.

The engine specifications of this design were purposely made the same as those of the engine reported in reference 6 in order to illustrate the knowledge of the engine necessary for an intelligent design. From reference 6, the engine has a conductivity of 0.06 and requires a Δp of 25 pounds per square foot for adequate cooling at full power. These values complete the information necessary for design.

Inasmuch as the engine is geared, the clearance between the cylinders and the propeller is sufficient to allow nose 1 to be used. The minimum cowling diameter (A, fig. 2) that can be used for this engine is 52 inches. The ordinates of the nose section calculated from figure 2 are as follows:

Station	b (in.)	a (in.)	Station	b (in.)	a (in.)	Station	b (in.)	a (in.)
1	0	39.5	6	4.16	48.4	11	9.88	51.3
2	.52	42.7	7	5.20	49.2	12	11.44	51.7
3	1.04	44.0	8	6.76	50.2	13	13.00	51.9
4	2.08	45.9	9	7.80	50.6	14	14.56	52.0
5	3.12	47.3	10	8.32	50.9			

It is desirable to locate the exit slot in a nonexpanding flow; the maximum cowling diameter should therefore not be decreased before the end of the exit passage. From that point the nacelle should fair smoothly into the wing surface, care being taken to keep the angle of convergence small to prevent any breakaway of flow.

Next compute the dimensions of the slot.

From figure 4

q at 200 m. p. h. = 102.5 lb./sq. ft.

q at 170 m. p. h. = 74 lb./sq. ft.

Then

$$\frac{\Delta p}{q}=0.24 \text{ and } 0.34, \text{ respectively.}$$

From figure 3

$$\frac{K}{K_2}=1.78 \text{ and } 1.40, \text{ respectively.}$$

Given

$$K=0.06.$$

Then

$$K_2=\frac{K}{K/K_2}=\frac{0.06}{1.78}=0.034 \text{ at 200 m. p. h.}$$

and

$$=\frac{0.06}{1.40}=0.043 \text{ at 170 m. p. h.}$$

The area of the slot is

$$K_2F=0.034\times 14.75=0.50 \text{ sq. ft.}$$

and

$$=0.043\times 14.75=0.63 \text{ sq. ft.}$$

The distance around the nacelle is $52\pi=163$ in.

If the slot extended completely around the nacelle, the openings would be approximately $0.50\times 144/163=0.44$ inch for cruising and $0.63\times 144/163=0.56$ inch for climbing.

As such a small area is required for cooling, it may be desirable to exhaust all the air over the upper surface of the wing. If the slot is extended halfway around the nacelle, the opening will be doubled. For ground operation, the skirt can be moved forward approximately 6 inches, giving an effective opening of approximately 3 inches. The slot area would then be

$$\frac{3}{144}\times\frac{163}{2}=1.7 \text{ sq. ft.}$$

or

$$K_2=\frac{1.7}{14.75}=0.115$$

and

$$\frac{K}{K_2}=\frac{0.06}{0.115}=0.52$$

From figure 3, the available $\Delta p/q=0.78$, or sufficient cooling would be available at

$$q=\frac{25 \text{ lb./sq. ft.}}{0.78}=32 \text{ lb./sq. ft.}$$

which corresponds to an air speed of 113 miles per hour.

It is probable that more cooling will be obtained than is shown by this computation for low speeds, which assumes an available pressure drop across the entire cowling equal to the dynamic pressure of the air stream. With the slot located above the wing and in the propeller slipstream, the pressure available for cooling at low air speeds will probably be increased in the order of 10 percent.

DRAG COMPUTATIONS

The drag associated with the design must now be computed. The drag may be divided into two parts: (1) the cooling drag defined in the discussion as ΔC_D, and (2) the basic drag or the drag of the basic shape of the cowling without cooling air flowing through it.

Cooling drag.—From figure 6, where

$$\frac{\Delta p}{q}=0.24 \text{ and } K=0.06$$

$$\Delta C_D=0.006$$

$$\Delta D=0.006\times 102.5\times 14.75=9 \text{ lb.}$$

and where

$$\frac{\Delta p}{q}=0.34 \text{ and } K=0.06$$

$$\Delta C_D=0.012$$

$$\Delta D=0.012\times 74\times 14.75=13 \text{ lb.}$$

The cooling horsepower for 200 miles per hour

$$=\frac{\Delta C_D qFV}{375}$$

$$=\frac{0.006\times 102.5\times 14.75\times 200}{375}=5 \text{ hp.}$$

and for 170 miles per hour

$$=\frac{0.012\times 74\times 14.75\times 170}{375}=6 \text{ hp.}$$

Drag of the basic shape. The computation of the drag of the basic cowling shape is a little more difficult and indirect; it depends on the interrelation of the nacelle, the propeller, and the wing. A rough estimation of this drag will be made in order to illustrate the example, but any particular case will require more detailed analysis of all the component parts.

The position as indicated in figure 2 was chosen from reference 7 as the most efficient location of the nacelle on the wing. The drag coefficient of the basic shape of the nacelle alone is given as $C_{D_0}=0.1193$. From reference 7, table XI, the effective nacelle drag divided by the drag of the nacelle alone equals 38 percent, or

$$\text{effective } C_{D_0}=0.38\ (0.1193)=0.045$$

which gives a basic drag at 200 miles per hour of

$$D_0=0.045\times 102.5\times 14.75=68 \text{ lb.}$$

or total drag $D=D_0+\Delta D=68+9=77$ lb.

The power required to overcome this drag is:

$$\text{hp.}=\frac{DV}{375}=\frac{77\times 200}{375}=41 \text{ hp.}$$

The primary purpose of this report is to present a method of obtaining the best cowling and not to present a method of performance calculation; the intricate performance problem of propeller, nacelle, and wing will therefore not be discussed further.

EXAMPLE II

DESIGN COMPUTATIONS

Airplane type: Military pursuit landplane.
Number of engines: 1.
Top speed of airplane: 300 m. p. h.
Climbing speed: 150 m. p. h.

Engine diameter: 54½ in.
Engine power:
Take-off: 1,000 hp. at 2,100 r. p. m.
Continuous: 850 hp. at 2,100 r. p. m.
Cruising: 600 hp. at 1,900 r. p. m.
Number of cylinders: 9.
Type of baffle: Commercial.
Propeller drive: Geared.
Maximum diameter of fuselage: 5 ft.
$K=0.10$.
Required $\Delta p=40$ lb./sq. ft.

The design of the nose section will be similar to example I; the ordinates are given in the following table. The minimum cowling diameter that will enclose the engine is 55 inches.

Station	b (in.)	a (in.)	Station	b (in.)	a (in.)	Station	b (in.)	a (in.)
1	0	41.7	6	4.40	51.2	11	10.45	54.3
2	.55	45.2	7	5.50	52.1	12	12.10	54.7
3	1.10	46.6	8	7.15	53.1	13	13.75	54.9
4	2.20	48.6	9	8.25	53.6	14	15.40	55.0
5	3.30	50.0	10	8.80	53.8			

The computations for the slot dimensions are:
From figure 4

$$q \text{ at } 300 \text{ m. p. h.} = 230 \text{ lb./sq. ft.}$$
$$q \text{ at } 150 \text{ m. p. h.} = 58 \text{ lb./sq. ft.}$$

Given

$$\Delta p = 40 \text{ lb./sq. ft.}$$

Then

$$\frac{\Delta p}{q} \text{ at } 300 \text{ m. p. h.} = \frac{40}{230} = 0.17.$$

$$\frac{\Delta p}{q} \text{ at } 150 \text{ m. p. h.} = \frac{40}{58} = 0.69.$$

From figure 3

$$\frac{K}{K_2} = 2.23 \text{ and } 0.66, \text{ respectively.}$$

Given

$$K = 0.10.$$

Then

$$K_2 = \frac{0.10}{2.23} = 0.045 \text{ at } 300 \text{ m. p. h.}$$

and

$$= \frac{0.10}{0.66} = 0.15 \text{ at } 150 \text{ m. p. h.}$$

Area of slot

$$K_2F = 0.045 \times \frac{55^2}{144}\frac{\pi}{4} = 0.045 \times 16.5$$
$$= 0.74 \text{ sq. ft. at } 300 \text{ m. p. h.}$$

and

$$0.15 \times 16.5 = 2.48 \text{ sq. ft. at } 150 \text{ m. p. h.}$$

$$\text{Slot opening} = \frac{\text{slot area}}{\text{circumference}} = \frac{144 \times 0.74}{55\,\pi}$$
$$= 0.62 \text{ in. at } 300 \text{ m. p. h.}$$

and

$$\frac{144 \times 2.48}{55\,\pi} = 2.07 \text{ in. at } 150 \text{ m. p. h.}$$

DRAG COMPUTATION

Cooling drag.—From figure 6

$$\text{at } \Delta p/q = 0.17 \text{ and } K = 0.10$$
$$\Delta C_D = 0.0067$$
$$\text{at } \Delta p/q = 0.69 \text{ and } K = 0.10$$
$$\Delta C_D = 0.052$$
$$\Delta D = \Delta C_D qF = 0.0067 \times 230 \times 16.5 = 25 \text{ lb.}$$

and

$$\Delta D = 0.052 \times 58 \times 16.5 = 50 \text{ lb.}$$

$$\text{The cooling power} = \frac{25 \times 300}{375} = 20 \text{ hp.}$$

and

$$= \frac{50 \times 150}{375} = 20 \text{ hp.}$$

Drag of the basic shape.—The basic drag of the engine cowling can be computed quite accurately if the value of the drag of the airplane with a streamline nose shape is known.

In reference 3, the drag coefficient for the nacelle with streamline nose shape is given as $C_D=0.0861$ and the drag coefficient for the same nacelle with an engine cowling on the front and zero cooling air is $C_D=0.1193$. The difference between these two coefficients, 0.1193−0.0861=0.0332, is the drag coefficient corresponding to the increase in drag due to the cowling.

This same increase in drag could be expected when an engine cowling replaces the streamline nose of the fuselage. The additional drag of the airplane due to the cowling is then

$$0.0332qF = 0.0332 \times 230 \times 16.5 = 126 \text{ lb.}$$

and

$$0.0332 \times 58 \times 16.5 = 32 \text{ lb.}$$

The total cowling drag at 300 m. p. h. is

$$\text{Basic drag} + \text{cooling drag} = 126 + 25 = 151 \text{ lb.}$$

and at 150 m. p. h. = 32 + 50 = 82 lb.

Some additional examples are presented in table I. Only the cooling drag and horsepower are given in the table because the computation of the basic drag depends on many factors not easily computed.

CONCLUDING REMARKS

1. The ordinates for two nose shapes that can be applied to most cowling designs are given.

2. A method of obtaining the dimensions of the exit of a cowling is presented.

3. An evaluation of the increment of drag associated with the flow of cooling air through the engine is given.

4. An evaluation of the increment of drag associated with the addition of an engine cowling to the nose of a streamline fuselage is given.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *March 5, 1938.*

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TABLE I.—EXAMPLES OF COWLING DESIGN

	Given				Level flight					
	Top speed (m. p. h.)	Δp (lb. per sq. ft.)	K	Climbing speed (m. p. h.)	q (lb. per sq. ft.)	$\frac{\Delta p}{q}$	ΔC_D	hp. to cool for F = 14.75 sq. ft.	$\frac{K}{K_2}$	Area of slot (sq. ft.)
1	150	20	0.05	110	58	0.35	0.010	3	1.37	0.54
2	150	40	.10	110	58	.70	.054	19	.65	2.27
3	230	20	.05	120	135	.15	.002	2	2.42	.30
4	230	40	.10	120	135	.30	.015	18	1.53	.96
5	230	60	.10	120	135	.44	.026	32	1.12	1.32
6	300	20	.05	150	230	.09	.001	3	3.15	.23
7	300	40	.10	150	230	.17	.007	19	2.33	.66
8	300	60	.10	150	230	.26	.012	33	1.69	.87
9	300	80	.10	150	230	.35	.019	52	1.37	1.08

	Climb					
	q (lb. per sq. ft.)	$\frac{\Delta p}{q}$	ΔC_D	hp. to cool for F=14.75 sq. ft.	$\frac{K}{K_2}$	Area of slot (sq. ft.)
1	31	0.65	0.030	4	0.73	1.01
2	31	1.29				
3	37	.54	.022	4	.92	.80
[1] 4	37	1.15	.217	37	.22	6.71
5	37					
6	58	.35	.010	3	1.37	.54
7	58	.70	.054	19	.65	2.27
[1] 8	58	1.04	.134	46	.31	4.76
9	58	1.39				

[1] Flaps.

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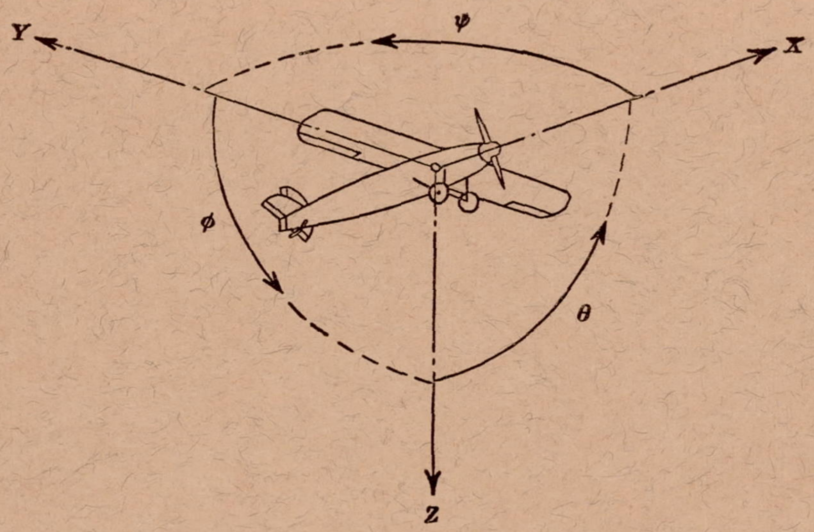

Positive directions of axes and angles (forces and moments) are shown by arrows

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 $=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

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.