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GENERAL ANALYSIS OF AIRPLANE RADIATOR PROBLEMS

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NATIONAL ADVISORY COMMITTEE
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GENERAL ANALYSIS OF AIRPLANE RADIATOR PROBLEMS.

By H. C. Dickinson, W. S. James and R. V. Kleinschmidt.

The objects of this report are (1) to present the analysis of the problem on which the experimental work conducted at the Bureau of Standards is based, (2) to explain the technical terms used in the work, and (3) to show the relations between the various parts of the work which are dealt with in detail in other reports.

The function of a radiator is to dissipate heat, but while doing so, it will have certain adverse effects on the plane on which it is mounted. First, it will add to the weight; second, the conditions for obtaining the best transfer of heat from the metal surface to the air require that the air shall flow rapidly past the surface, and this condition causes head resistance: third, certain positions of mounting on the plane seriously obstruct the view of the pilot or observer. A fourth factor of special importance in military airplanes is vulnerability and liability to injury, either from accident or from enemy bullets. The last two factors, not being capable of measurement, have not been considered in this investigation.

STATEMENT OF THE PROBLEM.

The problem of design therefore becomes one of determining the type of structure, and the location on the plane, that shall give the radiator the cooling capacity required for the engine with which it is to be used, and at the same time shall result in a minimum adverse effect on the plane. The adverse effects due to weight and head resistance will be represented by the power absorbed in lifting and sustaining the weight and in overcoming the head resistance, and the fundamental criterion for an airplane radiator will be that its absorption of power shall be low, when it is of such size as to dissipate the required amount of heat.

It is necessary to state with some care what is meant by "power absorbed chargeable to the radiator." If it were possible to build and operate a plane without any radiator (or other construction to perform its function), a certain amount of power would be required to drive the plane through the air at a given speed. But the addition of the radiator may necessitate alterations in structure (such as the substitution of a flat-nose radiator for a stream-line nose or the enlargement of the fuselage in order to accommodate the radiator required), which will make the resistance of the plane greater than in the former case; and the radiator itself will add to the weight of the plane and will offer resistance to passage through the air. The difference between the power required to drive the plane as equipped with the radiator and that required to drive it at the same speed when designed without a radiator is the power absorbed chargeable to the radiator. It includes power absorbed due to (1) weight of the radiator; (2) pressure difference producing flow of air through the radiator (i. e., the head resistance of the core); (3) any increase in the resistance of the fuselage or other parts of the plane caused by changes in the condition of air flow around the parts, or by changes in the structure necessitated by the radiator; (4) pressure necessary to produce water flow through the radiator. Items (2) and (3) together constitute the head resistance chargeable to the radiator, as distinguished from the head resistance of the core. In the case of a nose radiator there is not only a change in the condition of air flow due to the air which passes into the fuselage and out through the louvres, but also a change in form of the fuselage, due to the flat (and sometimes enlarged) nose required to accommodate the radiator.

THREE METHODS OF ATTACK.

There are three ways in which the problem may be attacked, namely:

1. A study of complete radiators on planes.
2. A study of types of radiator core and the methods of generalizing results to obtain the properties of complete radiators.
3. A study of the properties of single tubes, cells, or plates.

The first of these has been the basis of cut-and-try methods of determining whether a radiator will cool or not, but it has not been possible to consider the adverse effect on the plane by this method, except roughly. Weight is the only factor that can easily be measured, and it is found that in determining the power absorbed, weight may be of but small importance in comparison with head resistance. Although it might be possible to work out a method whereby complete data could be obtained from tests in flight, the expense and difficulty of making the necessary large number of tests on planes is so great that a simpler method has been chosen, which will allow a large number of types of core to be tested under widely varying conditions of use.

The study of types of core has therefore been selected as the basis of the experimental work, to be supplemented by such work on complete radiators in planes as may be required to verify the conclusions reached, and furnish needed data on the effect of location on performance. It has also been found advisable further to simplify certain portions of the work by studies on single tubes and plates.

The object of a laboratory study of types of core is to determine:

1. The structural characteristics of the core which determine its performance in any particular case, and the effect of these characteristics on performance.
2. The properties, or behavior, of the core when subjected to various conditions of use.
3. The conditions under which the core will operate when it is a portion of a radiator in any particular location on a plane.

STRUCTURAL CHARACTERISTICS OF A CORE.

The characteristics of a core which determine its behavior under given conditions of use have been taken to be:

1. Form and dimensions of air and water passages.
2. Depth of the core (measured in the direction of the air flow).
3. Kind and thickness of metal.
4. The portion of the frontal area which is open to allow the passage of air through the core, called "free area of the air tubes."
5. Extent and nature of cooling surface.

As an example of the way in which these factors influence the performance of the core, the following may be noted. As the depth of a core is increased the effectiveness of the cooling surface decreases owing to the rise in the temperature of the air as it passes through the air tubes, and the consequent decrease in temperature difference between the surface and the air. At the same time the amount of air that will flow through a tube decreases as the depth increases, tending further to reduce the cooling per unit surface. On the other hand, the total amount of cooling surface per unit of frontal area is increased, and at a much smaller cost in head resistance than would be the case if the frontal area were increased. Many of the effects of structural characteristics are governed by well-established laws so that a mathematical theory can be developed to predict their magnitude.

PROPERTIES EXPRESSING THE BEHAVIOR OF A CORE.

The properties of a core which express its performance are the following:

1. *Energy dissipated* (heat transfer or cooling capacity).—Since heat may be expressed in units of work, the rate of dissipation of heat may be expressed in units of power. It has been expressed in horsepower per square foot of frontal area, at any given air speed, for the con-

ditions of turbulent water flow and a temperature difference of 100° F. between the water and air, as defined below.

2. *Weight* of the core, and of the water contained, are important properties, being directly involved in the computation of horsepower absorbed.

3. *Head resistance of the core,* the force required to push it through the air, must be distinguished from head resistance *chargeable to the radiator* (defined above), which is the part of the over-all resistance of the plane caused by the radiator and any modifications of structure that the radiator may make necessary.

4. *Mass flow constant.*—It is found for all ordinary types of core that, when supported in a free air stream, the amount of air that passes through the core is proportional to the free air speed (at constant density), and therefore is proportional to the mass of air that would pass through the area occupied by the core if the core were removed. The fractional part of the air approaching the core, which actually passes through its air tubes, has been called the mass flow constant of the core. It is an important property, since the heat transfer and the head resistance are both closely related to it.

5. The *power absorbed* by a core may be computed from the head resistance and the weight as follows:

(a) If the total weight and the total available power (at the propeller) are known for the plane, the power absorbed by the weight of the core can be found approximately, and to this must be added the power required to overcome the head resistance, the latter being obtained directly from the head resistance and the speed of the plane.

(b) If the lift-drift ratio of the plane is known, it is simpler to divide the weight by this ratio, and thus reduce it to equivalent head resistance; i. e., drag on the wings and structure required to carry the weight, and to add this to the head resistance before multiplying by the plane speed to obtain the power absorbed.

In either case, it should be borne in mind that the power so computed is not necessarily equal to the power chargeable to the radiator, but is subject to the same limitations as the head resistance, as noted above. This method, which is intended to give a basis for comparison between cores, gives only an approximation. The British have shown by a very careful analysis the effect on a plane of small additions of weight and resistance, and it is shown that their relative importance varies greatly, according as top speed or rate of climb is given greater weight. This, of course, is due to the change in lift-drift ratio under various conditions.

6. *Figure of merit.*—In order to obtain a quantity by means of which the performance of various cores can easily be compared, it is necessary to consider both the energy dissipated and the power absorbed. The rate at which a radiator dissipates heat per unit power absorbed is a measure of the suitability of the radiator for airplane use so far as these two factors are concerned. This quantity has been called the figure of merit. The figure of merit will be the criterion for a radiator in any position, provided the power absorbed is the total power absorbed chargeable to the radiator as defined above. Unfortunately it is necessary to limit the definitions of head resistance *of a core* and power absorbed *by a core* to very specific conditions of use which can be accurately reproduced in the laboratory, so that it is only when the air flow around the radiator is not obstructed by other parts of the plane that the figure of merit *of a core* is of value in determining the figure of merit *of a radiator.*

CONDITIONS OF USE.

The conditions of use which affect the performance of the radiator, have been chosen not only to give the most accurate description of the factors which really determine the properties, but also to allow of easy comparison with the conditions found in flight. They are the following:

1. The *mass flow of air* through the core. This is defined as the mass of air that flows per second through the air tubes of a section of core of one square foot frontal area. This use of the term "mass flow" is identical with the common use of the term in the works of Osborne Reynolds and others, if the radiator is regarded as a structure through which air flows, and no account is taken of the fact that the flow is made up of a flow through a number of small tubes.

A careful distinction is made between the velocity of the air approaching the radiator (free air speed) and the mass flow through the core. It is the latter quantity that determines the effect of air velocity on heat transfer. It should be noted that the flow of air through the core depends upon many factors besides the free air speed.

2. *Temperature difference* between air and water. Strictly speaking, the heat transfer is determined by the mean over the entire core, of the temperature difference between the air and the water, at each small element of cooling surface. It can be shown, however, that for a given radiator under constant conditions of air flow and water flow, except that the air and water temperatures vary, the heat transfer is very nearly proportional to the difference between the mean temperature of the water and the temperature of the entering air. The water temperature depends, however, on the total length of the core, as well as upon the rate of flow through the core, so that it is much simpler to use the mean water temperature. The logarithmic mean should theoretically be used, but as the arithmetic mean differs from it very slightly under ordinary conditions of use it has been employed to save labor. The temperature difference under which a core works is given, then, as the difference between the temperature of the entering air and the mean of the temperatures of the entering and leaving water.

3. *Air density.*—Results have been reduced to a "standard" air density of 0.0750 pounds per cubic foot (0.001201 grams per cc; approximately density of dry air at 20° C., 78° F.).

4. *Flow of water* may be expressed in two ways, in quantity units, and in linear velocity through the tubes. The quantity of water flowing affects the drop in temperature of the water in passing through the radiator, while the linear velocity determines to some extent the rate of heat transfer.

5. The *mechanical condition of the air and water* in the tubes of the core is of considerable importance in determining its performance. If there is turbulent flow, the heat transfer will be by convection and can be much more rapid than in the case of streamline flow. On the other hand it is necessary to impart considerable energy to a fluid in order to produce turbulence, and this means an increased absorption of power by the radiator.

GENERALIZATION OF THE PROPERTIES OF A CORE TO OBTAIN THOSE OF A COMPLETE RADIATOR.

In considering the relations between the conditions under which a section of core operates when in a complete radiator, and the test conditions used in the laboratory, there are seen to be two general classes of locations in which a radiator may be placed on a plane. When the air flow around and through the radiator is not affected by the surrounding portions of the plane, the radiator is said to be in an *unobstructed position*. In this case there is no reciprocal effect of the radiator on the other parts of the plane, and the properties of a radiator in such a position may be computed from the results of laboratory tests.

When the air flow through the radiator is affected by other parts of the plane, it is said to be in an *obstructed position*. Such a radiator has a marked effect on the properties of surrounding portions of the plane, and the effects chargeable to it are not related in a simple manner to the properties of its core.

In order to obtain the properties of a radiator when in place from the properties of the core as determined by laboratory tests, it is necessary to know (1) the conditions of use of each part of the core, i. e., air flow, water flow, and temperatures; (2) the effect of headers, piping, etc.; and (3) the reciprocal effect of the radiator (especially the air flow through it) on other parts of the plane.

AIR FLOW THROUGH THE RADIATOR.

The mass flow of air through a radiator in an unobstructed position may be obtained directly from the mass flow constant of the core, the free air speed to which the core is subjected, and the air density. The free-air speed will usually be the plane speed, augmented by any effect of the propeller-slip stream. For a radiator in an obstructed position, the mass flow of air can not easily be computed. It is hoped to make measurements of this mass flow in obstructed positions in a series of tests in flight.

TEMPERATURE DIFFERENCE.

As noted above, the temperature difference selected for expressing the energy dissipated was so chosen that the results can be applied at once to a radiator of any size by using the mean temperature of the water. The latter may be found from the entering temperature, the amount of heat to be dissipated, and the water flow. It is therefore possible to regard an entire radiator as having a mean temperature, and as the air entering all parts of the radiator will commonly have the same temperature, the mean temperature difference for the radiator is easily found.

FLOW OF WATER.

The linear velocity of the water in the tubes determines the turbulent condition of the flow and should be kept above a certain value for each type of core. The total quantity of water flowing per unit time determines the temperature drop in the water, and thus affects the temperature difference.

ENERGY DISSIPATED.

The laboratory tests of a core will give the energy dissipated under "standard" conditions for a unit frontal area of core, and for any mass flow. If the mass flow is known, the total heat dissipated will be found from the test results and the frontal area of the core. Conversely, if the heat to be dissipated is known, the required frontal area of core can be determined. The amount of heat to be dissipated is a subject that will bear some study under actual flight conditions. In particular, the effect of the air that passes through a nose radiator, in cooling directly the walls of the engine jackets, should be determined, for it is an effect with which the radiator (or the position) should be credited.

HEAD RESISTANCE.

The head resistance of a radiator placed in an unobstructed position may be obtained directly from that of the core. It is roughly proportional to the frontal area, but includes the effect of headers and connections. For an obstructed position, if the mass flow of air is known, the head resistance *of the core* will be the same as that given in an unobstructed position when at such a speed as gives the same mass flow. But this value represents only that part of the total resistance chargeable to the radiator which is due to the pressure difference on its two faces. The resistance which other parts of the plane offer to the air which has passed through the radiator may be very considerable. Also, if the front of the fuselage has to be enlarged in order to accommodate a large nose radiator, this may cause a very great increase in the resistance of the fuselage, all of which is chargeable to the radiator. The resistance of obstructed radiators requires special study.

POWER ABSORBED.

The power absorbed by an unobstructed radiator may be obtained from that of the core as given, by a laboratory test with corrections for headers and connections. Since, however, it depends upon the lift-drift ratio of the plane (it has been computed for a ratio of 5.4), a special computation using the actual lift-drift ratio of the plane will give a better value. The values given with the results of tests are intended chiefly for comparative purposes. In obstructed positions the power absorbed must be specially determined.

FIGURE OF MERIT.

The figure of merit of a radiator in an unobstructed position will for comparative purposes be equal to that of the core. For obstructed positions it must be specially computed. It will always be less than that of the same radiator in an unobstructed position with the same mass flow of air.

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