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RADIATOR DESIGN

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SUMMARY

A design chart in coefficient form is presented from which a radiator can be chosen with any desired characteristics, whether for minimum power, particular dimensions, or pressure drop for cooling. The chart is a convenient tool for selecting a practicable radiator for any given set of operating conditions. Because the flow is turbulent in the tubes, the chart is for turbulent-flow conditions.

INTRODUCTION

For the past few years the NACA has been making a study of the heat-transfer problem as related to radiators and intercoolers. The existing information on heat transfer and the results of tests for an analysis of the radiator problem, conducted by the NACA at Langley Field, Va., are given in reference 1, which also presents an extensive bibliography of the literature on the subject. In reference 1 the optimum radiator was selected for a design pressure drop. It was shown further that, as the pressure difference across the radiator is lowered, the power for cooling is reduced.

Since reference 1 was prepared, the study of the radiator problem has been continued. An unpublished analysis made at the Laboratory showed that an optimum volume exists for a given set of design conditions, which is constant in the practical range of pressure drops and mass flow of cooling air. Equations determining the radiator were developed in an unpublished work and the design chart presented in this paper was prepared by use of those equations.

SYMBOLS

A   open frontal area of radiator, square feet

C   a constant representing the power required to carry unit open radiator volume

$$\left(C = \epsilon \frac{C_D}{C_L} \rho_r V_o \right)$$

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C_1 dimensionless constant   (0.0247)

C_2 dimensionless constant   (0.049 = $2C_1$)

c_p specific heat at constant pressure, Btu per pound per degrees Fahrenheit

C_D drag coefficient of the airplane

C_L lift coefficient of the airplane

D hydraulic diameter of radiator tube, foot

g acceleration of gravity, feet per second per second

H total heat dissipation of radiator, Btu per second

$$K_1 = \frac{2C_2\, C_L\, \rho\, V_0^{2}}{\varepsilon\, C_D\, \rho_r\, D\, R_0^{0.8}}$$

$$K_2 = \frac{\varepsilon\, C_D\, \rho_r\, g\, c_p (T_w - T_{1a})}{C_L\, V_0\, H}$$

L tube length, feet

M_c mass flow of cooling air

Δp pressure difference across radiator excluding end losses, pounds per square foot

P_T total power chargeable to radiator

q_t dynamic pressure $(\tfrac{1}{2}\rho\, V_t^{2})$

Q volume of cooling air, cubic foot per second

R Reynolds number in tube $\left(\dfrac{D V_t \rho}{\mu}\right)$

$$R_0 = R\,\frac{V_0}{V_t} = \frac{D V_0 \rho}{\mu}$$

T_w tube-wall temperature

T_{1a} temperature of air at entrance, $^\circ F$

T_o temperature of cooling air at outlet

v open volume of the radiator, feet   ($v = AL$)

V_o airplane speed, feet per second

V_t average velocity of air in radiator tube

ϵ dimensionless factor by which radiator weight is multiplied to account for additional airplane structure required

ρ air density, slugs per cubic foot

μ coefficient of viscosity, slugs per foot per second

ρ_r density of radiator based on open volume, pounds per cubic foot

ANALYSIS OF PROBLEM

General Analysis

Three equations determine the radiator:

$$P_T = \Delta p \, V_t \, A + CAL \tag{1}$$

$$H = \rho \, V_t \, A_b \, c_p (T_w - T_{1a}) (1 - e^{-4C_1 R^{-0.2} L/D}) \tag{2}$$

$$\Delta p = 2C_2 \, \rho \, V_t^2 \, R^{-0.2} \, L/D \tag{3}$$

Equation (1) gives the total power used by the radiator as a sum of the power required to push the cooling air through the radiator and the power required to carry the radiator. The total heat transfer to the cooling air in terms of the mass flow and the temperature rise of cooling air is given by equation (2). Equation (3) expresses the pressure drop of the cooling air while passing through the radiator in terms of the air flow, the Reynolds number, and the ratio of the length to the diameter of the tube.

From equations (1), (2), and (3) the following functions used in making figure 1 were developed:

$$\Delta p' + \left(\frac{P'}{V'} - 1\right)^{\frac{5}{7}} \log\left(1 - \frac{\Delta p'}{P' - V'}\right) = 0 \qquad (4)$$

$$\Delta p' = \left(\frac{Q'}{V'}\right)^{\frac{5}{2}} \left[\log\left(1 - \frac{1}{Q'}\right)\right]^{\frac{7}{2}} \qquad (5)$$

$$\Delta p' = \left[\frac{A'\left(\frac{A'\Delta p'}{V'}\right)^{\frac{5}{9}}}{V'}\right]^{\frac{5}{2}} \left\{\log\left[1 - \frac{1}{A'\left(\frac{A'\Delta p'}{V'}\right)^{\frac{5}{9}}}\right]\right\}^{\frac{7}{2}} \qquad (6)$$

The primes used in these equations refer to the functional relations. The following expressions define further certain terms in the equations:

$$V' = V K_1^{\frac{5}{7}} K_2 \qquad (7)$$

$$\Delta p' = \Delta p \frac{K_1^{\frac{5}{7}}}{\rho V_0^2} \qquad (8)$$

$$P' = P_T \frac{K_1^{\frac{5}{7}} K_2}{\theta} \qquad (9)$$

$$A' = A \frac{K_1^{\frac{9}{14}} K_2 R_0^{0.2} D}{2\theta_2} \qquad (10)$$

$$Q' = Q \frac{K_1 K_2 R_0^{0.2} D}{2C_2 V_0} \qquad (11)$$

Design Chart

Equations (4), (5), and (6), respectively, determine the contour lines of P', Q', and A' that are plotted in

figure 1 on the coordinates of $\Delta p'$ and v'. If the problem is to select the radiator that will absorb the least power for an available pressure drop across the radiator, the line of least power is shown on the chart, drawn through the vertical tangent points of the P' curves. It should be noted that the v' values given by this line vary only from 1.30 to 1.50 over the entire range of $\Delta p'$, which indicates the possibility of a radiator of constant volume regardless of the pressure drop.

Minimum power is not always the most important consideration in the selection of a radiator. When other determining factors such as frontal area, volume, or mass flow are to be considered, it will be necessary to choose points not in the minimum power line. In any case, a radiator can be chosen from the chart for any set of conditions, and the cost in performance of the compromise made can be exactly determined.

If the volume of cooling air is used as a criterion for picking a radiator, the radiator would be larger and would require a smaller pressure drop. The Q' curves intersect the P' curves above and to the left of the apex of the P' curves. The A' curves intersect the P' curves at almost the same place as the constant $\Delta P'$ curves, that is, on the apex of the P' curves.

The use of such a chart is extremely simple. Suppose the pressure drop for cooling is known, then $\Delta P'$ can be computed from relation (3). The chart gives the value of v', P', A', and Q'. The volume can be computed from relation (7), the power from relation (9), the frontal area from relation (10), and the volume of cooling air from relation (11). The characteristics and the performance of the airplane, the altitude, and the heat dissipation are all included in the constants K_1 and K_2.

The chart (fig. 1) is the general solution of equations (1), (2), and (3). Equation (1) is straightforward, being subject to no limitations within itself. In equation (2) the assumptions have been made that T_w is a constant and that the Reynolds analogy holds. The first assumption causes no appreciable error in selecting an aircraft radiator.

The second assumption is true with turbulent flow when the pressure drop is due to skin friction alone. In equation (3) an analytical expression is used for the pressure

drop. This equation has been found to be true for long, straight tubes in which all the pressure loss with turbulent flow is due to skin friction and the entrance effect is small. Tubes having an L/D ratio less than 150 show a deviation from this formula but the deviation is not important for a ratio of L/D greater than 40. Equation (3) does not include the exit effect. The exit effect is a small pressure drop proportional to q_t and may be included just as logically with the duct losses as with the radiator pressure drop.

Equations (1), (2), and (3) are the same equations used in reference 1. Thus the chart based on these equations will make it possible to select a radiator with the same accuracy but with considerably less effort than was required in reference 1. This chart gives all the possible solutions and presents them as a unit. The entire analysis assumes turbulent flow. In all practicable cases the flow will be turbulent.

The chart applies only to the cold radiator. When the average velocity and the appropriate Reynolds number in the heated case are used, however, the results will be correct if Δp is increased by the amount of increase in momentum of the cooling air passing through the radiator. The same method was used in reference 1. Thus, with two or, at most, three trial pressure drops a radiator that has the desired Δp for the heated case, and that may include even the exit loss, can be selected.

SELECTION OF RADIATOR

Obviously many considerations, which must be decided before proceeding to the chart, enter into the selection of a radiator. Among the factors to be considered is the altitude. Ordinarily, the most difficult cooling case is at the critical altitude. In order to achieve maximum speed, it is desirable to design the radiator for this condition. If the radiator is chosen for cruising condition at the critical altitude, however, the case of full power climb at the critical altitude must be investigated to determine whether the available pressure drop is adequate for cooling. The dimensions of the radiator must also be considered. It is required that the radiator fit into the airplane with a minimum of effort and expense. In many cases the dimensions of the radiator are of almost equal importance with power and pressure drop.

In the final analysis, the selection of a radiator represents so many compromises that it would be futile to lay down definite rules for picking a radiator. All that can be hoped for is a clear picture of the problem. In this connection, it is of interest to choose a radiator for a given set of design conditions.

Heat dissipation, H - - - horsepower - - - - - - - - 500

Airplane speed, V_o - - - - miles per hour - - - - - - 400

Critical altitude - - - - feet - - - - - - - - - - 25,000

C_L/C_D - 14.0

Radiator tube diameter, D foot - - - - - - - - - - 1/48

Ethylene glycol-water,
  $T_w - T_{ia}$ - - - - - - - ^oF - - - - - - - - - - - 230

Δp for cooling - - - - - pounds per square foot - - - 30

Density, ρ_r - - - - - - pounds per cubic foot - - - 90

ϵ - 1.5

The following steps are used in selecting a radiator for minimum power:

$$K_1 = \frac{2 \times 0.049 \times 14 \times 0.001065 \times (588)^{-2}}{1.5 \times 90 \times \frac{1}{48} \times 8} = 22.5$$

$$K_2 = \frac{1.5 \times 90 \times 32.2 \times 0.24 \times 230}{14 \times 588 \times 352} = 0.0828$$

$$\Delta p' = \frac{30 \times 9.24}{366} = 0.755$$

From the chart

$$Y' = 1.375 \qquad A' = 1.92$$
$$Q' = 1.95 \qquad P' = 2.83$$

The open volume of the radiator

$$Y = \frac{1.375}{9.24 \times 0.828} = 1.80 \text{ cubic feet}$$

and the actual volume equals 2.70 cubic feet.

$$Q = \frac{2 \times 0.049 \times 583 \times 48 \times 1.95}{22.5 \times 0.0828 \times 3} = 353 \text{ cubic feet per second}$$

The open frontal area of the radiator

$$A = \frac{192 \times 2 \times 0.049 \times 43}{7.4 \times 0.0828 \times 8} = 1.85 \text{ square feet}$$

and the actual frontal area equals 2.77 square feet.

$$P_t = \frac{2.83 \times 5550}{9.24 \times 0.628 \times 550} = 53.0 \text{ horsepower}$$

$$\Delta p = 30$$

$$L = 12 \text{ inches}$$

$$M_c = 12.5 \text{ pounds per second}$$

$$T_o - T_{ie} = \frac{H}{M_c \, c_p} = \frac{500 \times 0.707}{12.5 \times 0.24} = 118^\circ \text{ F}$$

$$V_t = \frac{Q}{A} = \frac{353}{1.85} = 196 \text{ feet per second}$$

$$q_t = 20.4 \text{ pounds per square foot}$$

A momentum loss of 9.5 pounds per square foot and an exit loss (0.2 q_t) of 4.1 pounds per square foot must be added to the given pressure drop of 30 pounds per square foot. Heating the air causes a lower density and a higher velocity, which results in an increase in momentum, that is,

$$\rho \, V_t^2 \left(\frac{T_o - T_{ie}}{T_{ia}} \right) = 0.001065 \times (196)^2 \left(\frac{118}{435} \right) = 9.5$$

pounds per square foot. Thus, the over-all Δp across the radiator is approximately 44 pounds per square foot instead of 30, as desired. This increase in Δp increases the power required.

A second trial may be made, using a Δp of 20 pounds

per square foot, and a very close approximation will be made to the design choice of $\Delta p = 30$ pounds per square foot.

$$\Delta p' = \frac{20 \times 9.24}{366} = 0.504$$

From the chart

$$\psi' = 1.375$$
$$Q' = 2.4$$
$$A' = 2.45$$
$$P' = 2.55$$

The open volume of the radiator

$$V = \frac{1.375}{9.24 \times 0.328} = 1.80 \text{ cubic feet}$$

and the actual volume is 2.70 cubic feet.

$$Q = 446 \text{ cubic feet per second}$$

The open frontal area of the radiator

$$A = 2.36 \text{ square feet}$$

$$P_t = 3.64 \text{ feet actual frontal area} = 54.2 \text{ horsepower}$$

$$\Delta p = 20$$

$$L = 9.1 \text{ inches}$$

$$M_c = 15.4 \text{ pounds per second}$$

$$(T_o - T_{ia}) = 95^o \text{ F}$$

$$V_t = \frac{446}{2.36} = 189 \text{ feet per second}$$

$$q_t = \frac{1}{2}(0.001065) \times (189)^2 = 19.0 \text{ pounds per square foot}$$

Δp due to momentum drag $= 38.0 \times \dfrac{95}{495} = 7.0$ pounds per square foot

$\Delta'p$ due to exit drag $= 19 \times 0.2 = 3.8$ pounds per square foot

Δp total $= 20 + 7.0 + 3.8 = 30.8$

The problem of choosing the radiator for a given installation often becomes the problem of deciding which radiator of several is most suitable. In such a case, a table of radiator dimensions, including P_t, Δp, and L_e, should be made up, and the radiator should be chosen that most nearly approaches the optimum or that has some characteristic which makes it especially desirable.

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REFERENCE

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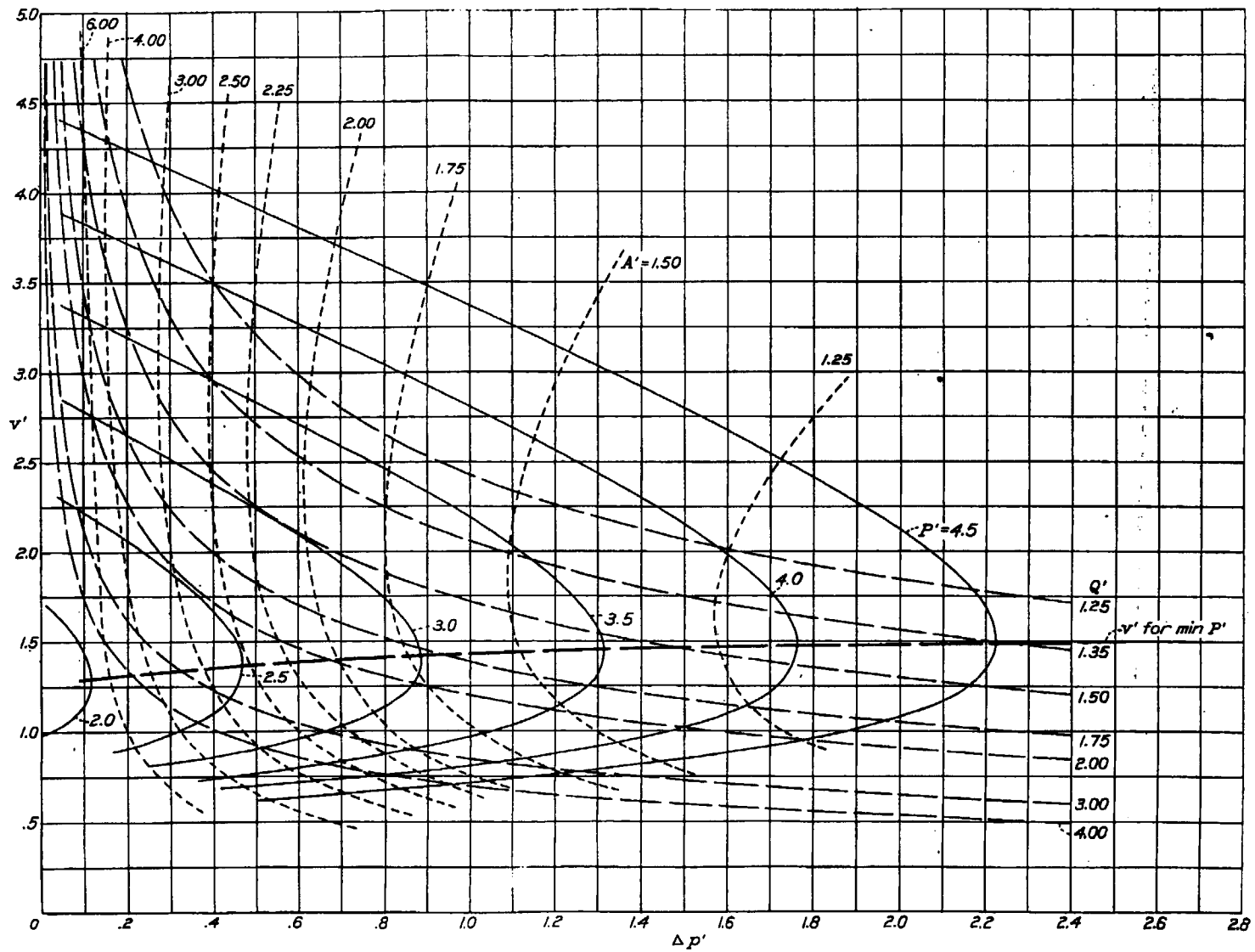   Installation. NACA confidential report, 1939.

Figure 1.- Generalized heat-transmission diagram.

Fig. 1