REPORT No. 784

INTERCOOLER COOLING-AIR WEIGHT FLOW AND PRESSURE DROP FOR MINIMUM DRAG LOSS

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SUMMARY

An analysis has been made of the drag losses in airplane flight of cross-flow plate and tubular intercoolers to determine the cooling-air weight flow and pressure drop that give a minimum drag loss for any given cooling effectiveness and, thus, a maximum power-plant net gain due to charge-air cooling. The drag losses considered in this analysis are those due to (1) the extra drag imposed on the airplane by the weight of the intercooler, its duct, and its supports and (2) the drag sustained by the cooling air in flowing through the intercooler and its duct. The investigation covers a range of conditions of altitude, airspeed, lift-drag ratio, supercharger-pressure ratio, and supercharger adiabatic efficiency.

The analysis reveals the following facts concerning the cooling-air operating conditions of intercoolers:

(1) The optimum cooling-to-charge-air weight-flow ratio, that is, the flow ratio that gives minimum drag loss, is only slightly dependent on the airplane flight conditions and the charge-air pressure drop and is mainly a function of the intercooler cooling effectiveness and the cooling-air pressure drop.

(2) When the cooling-to-charge-air weight-flow ratio is varied to maintain its optimum value, the cooling-air pressure drop is optimum between 1 and 3 inches of water; the variation within this range depends on flight conditions, charge-air pressure drop, and type of intercooler (plate, charge-across-tube, or charge-through-tube). Within this range of pressure drop the change in drag loss from the minimum value is slight.

The optimum values of cooling-air pressure drop and weight-flow ratio are tabulated. Curves are presented to illustrate the results of the analysis. Included are curves that give the variation in intercooler volume and the increase in drag loss incurred by a departure of intercooler operation from the optimum values of cooling-air pressure drop and weight-flow ratio.

INTRODUCTION

The advantages of charge-air cooling are dependent not only on the degree of cooling accomplished but also on the drag losses incurred by the intercooler. For any given cooling effectiveness, minimum drag of the intercooler results in maximum power-plant net gain due to the addition of the intercooler.

In the design of intercoolers, if the pressure required to force air through the passages were the only consideration, a large, heavy intercooler would minimize the drag loss. In aircraft added weight increases the airplane drag losses and it is therefore necessary that an intercooler be designed to effect a compromise between the intercooler cooling-air losses and the losses due to the intercooler weight. In making this compromise the designer can vary either the intercooler core structure or certain intercooler operating conditions. Although variation in core-structure dimensions is quite important in permitting changes in external dimensions for fitting an intercooler into the available space (references 1 and 2), it is of less importance in minimizing the drag losses. The designer has much more control over the drag losses through variation of such intercooler operating conditions as cooling-air weight flow and pressure drop. Changes in cooling-air weight flow and pressure drop are also accompanied by changes in external dimensions of the intercooler for a given core structure.

The drag losses due to the cooling-air flow and the intercooler weight can be expressed in terms of operating conditions, which fall into two classes: (1) intercooler operating conditions and (2) flight conditions. Class (1) consists of the cooling effectiveness and the weight flows and the pressure drops of the charge and the cooling air. Class (2) consists of altitude, airspeed, lift-drag ratio, supercharger efficiency, and pressure ratio. For the designer the flight-condition group is usually fixed. Of the intercooler operating conditions, the cooling effectiveness and the charge-air weight flow are usually predetermined; the designer is therefore free to choose, within limits, the cooling-air weight flow and pressure drop.

In this analysis the cooling-to-charge-air weight-flow ratio and pressure drop that give minimum drag loss have been determined for various conditions of flight and for various cooling requirements. The selection of an intercooler for a specific installation is, however, also a compromise between intercooler dimensions and intercooler drag loss. The designer is, in most cases, limited in the choice of the intercooler operating conditions by the space available in the airplane for the intercooler. Considerations of the charge-air and the cooling-air ducting also enter and complicate the entire picture. Thus, a design for minimum drag loss may, for a given installation, be prohibitive on the basis of installations in the airplane in spite of the variety of shapes and sizes of intercoolers made possible by changing the intercooler core-structure dimensions. Charts are presented that give the magnitude of the increase in drag and the change in intercooler volume resulting from a departure from the optimum conditions.

The optimum charge-air pressure drop has not been included in the analysis because the attendant losses depend to a large degree on the specific engine installation.

PROCEDURE

The cooling-air and transportation drag losses.—The equation for the cooling-air drag loss of an intercooler is derived in appendix B (equations (1) to (11)) from a consideration of the momentum change of the cooling air as it flows through the intercooler and the duct. The effect of the addition of heat to the cooling air in the intercooler is included in the derivation. This effect causes a slight reduction of the cooling-air drag loss and, for low values of cooling-to-charge-air weight flow M_1/M_2 and cooling-air pressure drop Δp_1, may even result in a thrust rather than a drag.

The increase in airplane drag resulting from the weight increase due to the addition of an intercooler is calculated as the drag of the additional airplane wing area required to keep the wing loading, and thus the take-off and landing speeds, constant. This additional drag loss is given by equations (12) to (18) of appendix B.

Because the two intercooler drag losses vary in opposite directions with variation of M_1/M_2 or Δp_1, it is expected that for certain values of these two operating variables the sum of the two drag losses is minimum. These optimum values of M_1/M_2 and Δp_1, denoted herein as $(M_1/M_2)_{opt}$ and $(\Delta p_1)_{opt}$, are determined by the procedure outlined in appendix B (equations (19) to (28)).

The parameter $(L/D)_{eq}$.—In this analysis it is convenient to make use of a parameter $(L/D)_{eq}$ relating the intercooler transportation costs to the heat-transfer surface area. This parameter is defined as

$$(L/D)_{eq}=\frac{L/D}{\left(\frac{\rho_m}{173}\right)\left(\frac{12t}{0.01}\right)\left(\frac{R_W}{1.2}\right)\left(\frac{y}{2}\right)\left(\frac{S}{S_0}\right)}$$

It should be noted that the parameter $(L/D)_{eq}$ includes the following variables in addition to the airplane-wing lift-drag ratio L/D:

(a) Density of the material of which the intercooler is constructed ρ_m

(b) Plate or tube-wall thickness t

(c) Ratio of weight of intercooler to weight of intercooler plates or tubes R_W

(d) Ratio of increase in airplane weight caused by the intercooler to the weight of the intercooler y

(e) Ratio of the heat-transfer surface area of the intercooler S to the surface area of a reference intercooler S_0

The symbols used in this report are listed in appendix A. The significance of the parameter $(L/D)_{eq}$ is given in more detail in appendix B.

The reference intercooler.—The relation among the heat-transfer surface area, the operating conditions, and the core structure is obtained from reference 1 for the plate intercooler and from reference 2 for the tubular intercooler. In references 1 and 2 the relation for each type of intercooler is first given for a reference intercooler, which is defined as one having a reference core structure. The variation in heat-transfer area with core structure for constant operating conditions is then given. This variation of heat-transfer area with core structure is the S/S_0 term included in the $(L/D)_{eq}$ parameter. The transportation loss is then, as shown in appendix B, a function only of $(L/D)_{eq}$, airplane velocity, and heat-transfer surface area of the reference intercooler.

The optimum M_1/M_2 and Δp_1.—The optimum values of M_1/M_2 and the related optimum values of Δp_1 were determined for extreme conditions of intercooler operation and airplane flight. The range of conditions covered in the investigation is:

Intercooler operating conditions:

Charge-air sea-level pressure drop (σ, air density relative to standard atmosphere; Δp_f, skin-friction pressure drop of air across intercooler) $\sigma_{av,2}\,\Delta p_{f,2}$, inches of water	2–12
Cooling effectiveness η, percent	30–85

Airplane flight conditions:

Altitude, feet	20,000–50,000
Dynamic pressure in flight q, inches of water	12.5–25
$(L/D)_{eq}$	5–20
Supercharger-pressure ratio r	1–3
Supercharger efficiency η_{ad}, percent	65–100

The duct efficiency was assumed constant at 90 percent.

Although the analysis was made for a range of $(L/D)_{eq}$ from 5 to 20, values above this range may be encountered in special cases because of the numerous variables included in the parameter. It can be stated that the results of the analysis presented herein also apply for values of $(L/D)_{eq}$ up to infinity because, when $(L/D)_{eq}$ is infinite, the drag loss is equal to only the loss due to the cooling air; plots of cooling-air drag loss against Δp_1 for optimum M_1/M_2 show optimum values of Δp_1 and M_1/M_2 that are in substantial agreement with values given for the range of $(L/D)_{eq}$ considered in this report.

RESULTS AND DISCUSSION

The results of the analysis outlined in appendix B may be simply represented for the foregoing practical range of conditions as

$$\left(\frac{M_1}{M_2}\right)_{opt}=\frac{be^{3.06\eta}}{\Delta p_1{}^m}$$

$$(\Delta p_1)_{opt}=1 \text{ to } 3 \text{ inches of water}$$

where b and m are constants, the values of which depend on the airplane flight and intercooler operating conditions. Because b and m do not critically vary over the range of conditions investigated in this report and because small changes in M_1/M_2 away from the optimum have very little effect on the drag loss, the factor b and exponent m may, for general design purposes, be assigned constant average values. These average values were determined as approximately $b=0.49$ and $m=0.36$ and will give M_1/M_2 values suitable for intercooler design on the basis of minimum drag loss.

Thus, when the system is operating at the optimum cooling-air pressure drop (from 1 to 3 in. water), the optimum ratio of cooling-air to charge-air weight flow is given from the foregoing equation as follows:

η (percent) ↓ \ Δp_1, in. water →	$(M_1/M_2)_{opt}$ 1	2	3
30	1.2	1.0	0.8
40	1.7	1.3	1.1
50	2.3	1.8	1.5
60	3.1	2.4	2.1
70	4.2	3.2	2.8
80	5.7	4.4	3.8

For any value of η within the range given in the table, a value of Δp_1 from 1 to 3 inches of water can be chosen without changing the drag loss an appreciable amount. There is a slight trend in favor of the low values of Δp_1 at high altitudes.

As previously emphasized, the space available in the airplane for the installation of the intercooler and its ducts is a consideration of primary importance in the selection of the cooling-air operating conditions. This consideration may make it necessary to deviate from the optimum cooling-air conditions. It is of interest to know how the dimensions of an intercooler change with variation in cooling-air conditions from their optimum values. This information may be obtained from references 1 and 2. A table based on the design information given in reference 1 has been prepared for the plate intercooler to illustrate the dimensional trends involved. For this table the plate intercooler is assumed to have 0.010-inch plates spaced 1/16 inch for the cooling-air-flow passages and 1/32 inch for the charge-flow passages. The intercooler is assumed to operate at a cooling effectiveness of 50 percent with a charge-air pressure drop of about 8 inches of water. The dimensions of this intercooler for various cooling-air operating conditions are given in table I.

TABLE I.—EFFECT ON INTERCOOLER DIMENSIONS OF CHANGING COOLING-AIR OPERATING CONDITIONS

Δp_1 (in. water)	M_1/M_2	Cooling-air flow length (in.)	Charge-air flow length (in.)	No-flow length (in. per lb/sec charge-air flow)	Core volume (cu. in. per lb/sec charge-air flow)
2 (*opt*)	1.8 (*opt*)	5.0	7.0	17.1	600
	2.5	3.5	6.2	22.4	490
6	1.2 (*opt*)	9.9	7.3	8.8	640
	2.5	4.4	5.3	16.7	390
10	1.0 (*opt*)	13.4	7.3	6.5	640
	2.5	5.0	4.9	14.2	350

Table I shows that, for a given core structure and for conditions of constant charge-air pressure drop and cooling effectiveness, an increase in M_1/M_2 from the optimum value for a given value of Δp_1 results in a reduction in intercooler volume, a reduction in cooling-air flow length, and an increase in the no-flow dimension. It is shown later in the report that for any value of Δp_1 an appreciable change in M_1/M_2 from the optimum gives only a small increase in drag loss. Choice of the higher values of Δp_1 for a given cooling-air weight flow leads to intercoolers having larger cooling-air flow lengths and smaller no-flow dimensions than for the optimum value of Δp_1.

The analysis of this report is based on computations from basic heat-transfer data on flat plates and banks of tubes. These same elements are used on commercial intercoolers. The data on commercial intercoolers cover only a limited range of sizes and a comprehensive analysis to determine the optimum cooling-air operating conditions was not possible. The few checks that could be made indicated agreement with the optimum values for cooling-air pressure drop and weight flow given by this report.

Figure 1 gives the variation in drag loss with cooling-air pressure drop for values of $\sigma_{av,2}\,\Delta p_{f,2}$ of 6 inches of water, of $(L/D)_{eq}$ of 10, and of q of 12.5 inches of water and for extreme values of intercooler cooling effectiveness and operation altitude. In this figure, M_1/M_2 was kept optimum throughout; that is, M_1/M_2 varied in such a manner that, for any set of conditions including Δp_1, the drag loss was a minimum. The optimum value of Δp_1 is shown by the curves to vary between 1.2 and 1.5 inches of water. Of particular interest is the flatness of the drag-loss curves in the neighborhood of the optimum Δp_1.

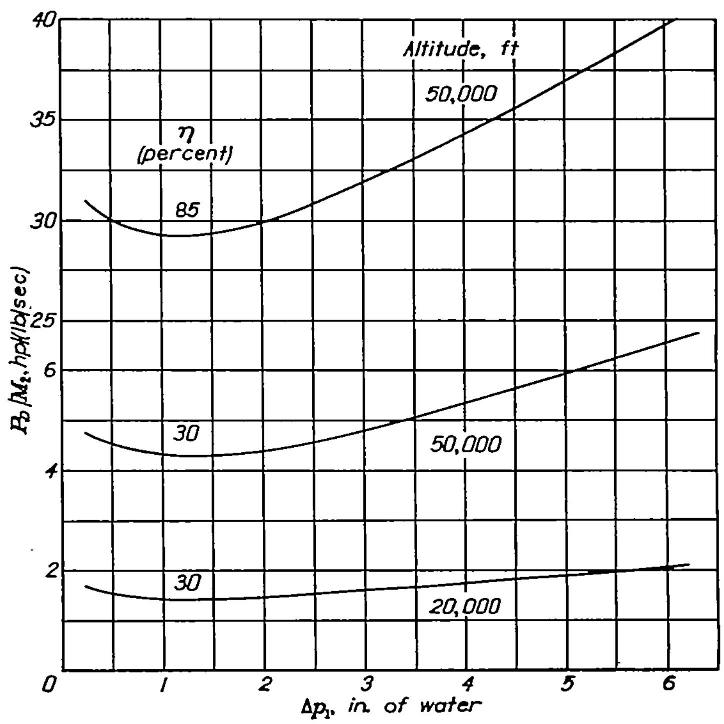


FIGURE 1.—Variation of plate-intercooler drag loss with cooling-air pressure drop for optimum cooling-air flow. $(L/D)_{eq}$, 10; q, 12.5 inches of water; $\sigma_{av}\,\Delta p_{f,2}$ 6 inches of water.

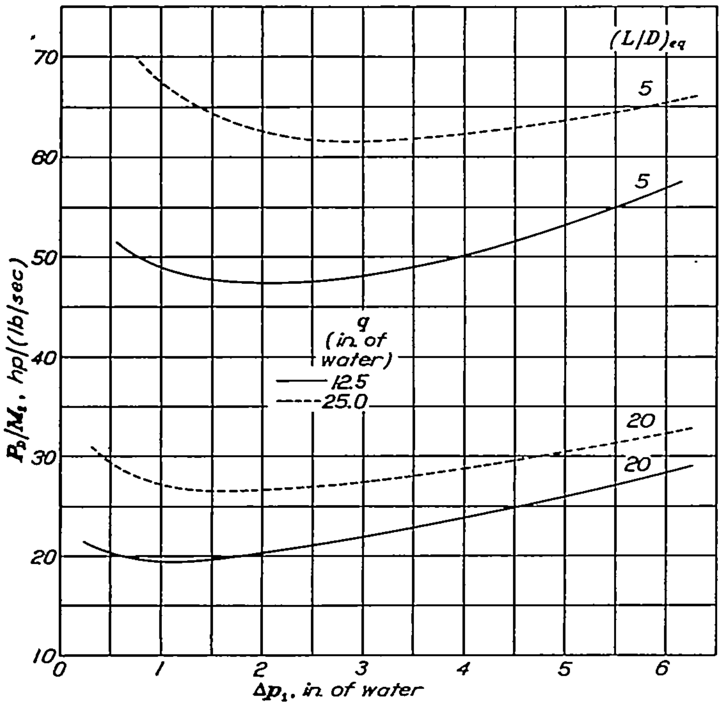


FIGURE 2.—Variation of plate-intercooler drag loss with cooling-air pressure drop for optimum cooling-air flow when $(L/D)_{eq}$ is 5 and 20, and q is 12.5 and 25 inches of water. Altitude, 50,000 feet; η, 85 percent.

In figure 2 is shown, for optimum M_1/M_2, the effect of $(L/D)_{eq}$ and airplane speed on the optimum Δp_1 at 50,000-foot altitude and 85-percent intercooler cooling effectiveness. It is seen that $(\Delta p_1)_{opt}$ lies between 1 and 3 inches of water and that little change from minimum drag is obtained for the conditions of $(L/D)_{eq}$ and airplane speed shown in the figure by operating the intercooler at an average cooling-air pressure drop of 2 inches of water. Plots similar to those of figures 1 and 2 made for numerous airplane flight and intercooler operating conditions show that, for the range of conditions investigated in this report, very little deviation from minimum drag occurred when operation is at cooling-air pressure drop of 2 inches of water.

The analysis outlined in appendix B for the plate intercooler also applies for the tubular intercooler provided the proper value of $(L/D)_{eq}$ is used. For a given set of intercooler operating conditions, the heat-transfer areas for the tubular intercooler and the plate intercooler are sufficiently equal (references 1 and 2) that the range of values of $(L/D)_{eq}$ covered by the curves of this report includes the range of interest for both types of intercooler. Thus the optimum values of Δp_1 and M_1/M_2 obtained from these curves should apply for both types of intercooler.

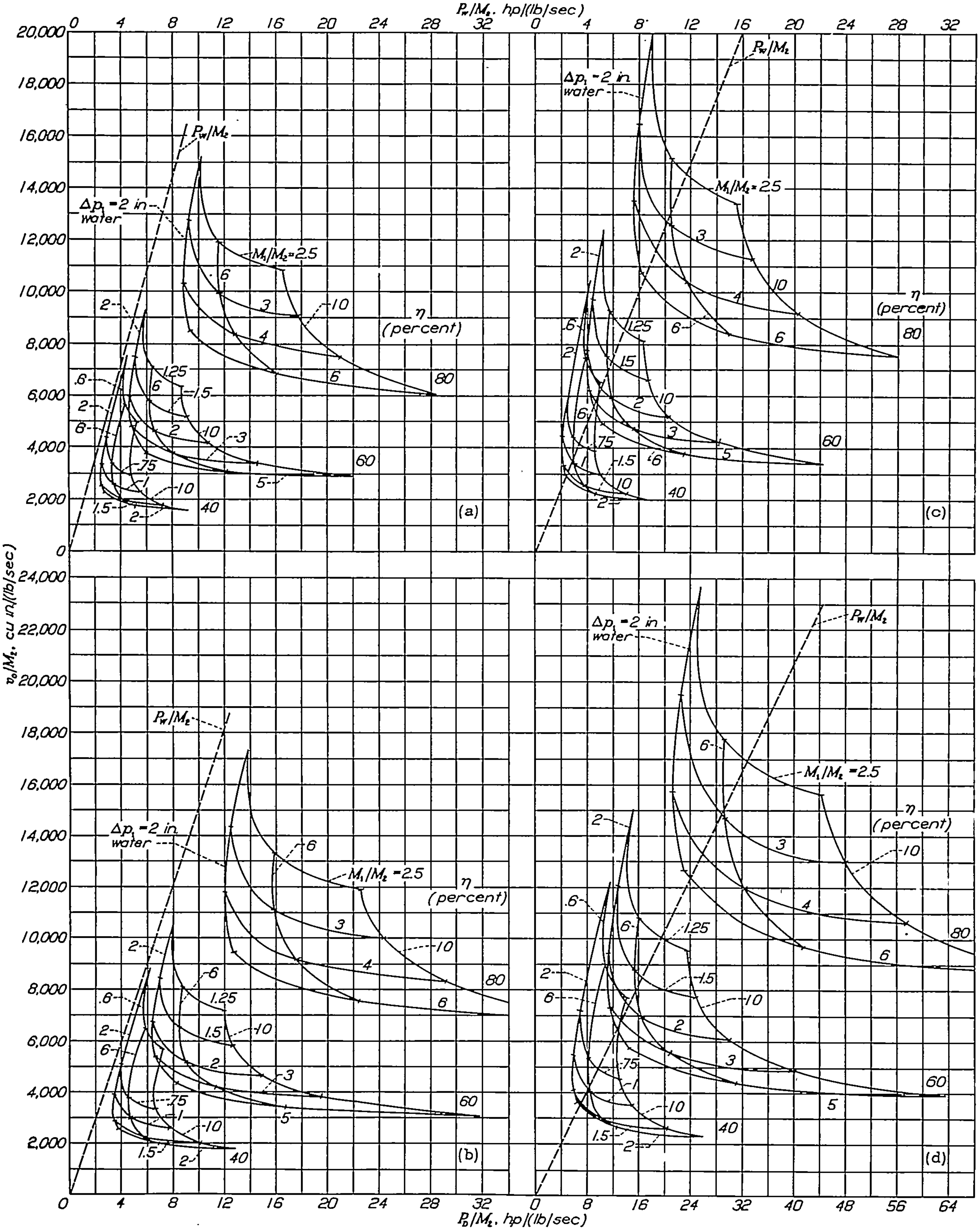
Figures are presented to assist the designer in choosing the intercooler cooling-air design conditions (Δp_1 and M_1/M_2) best suited to his particular purpose from considerations of volume as well as drag loss. These figures relate the intercooler drag loss to the volume of the reference intercooler for a wide range of flight and intercooler operations. Curves giving the variation in intercooler volume due to change in core structure from the reference structure are given in references 1 and 2. As pointed out previously, the effect of change in core structure on the drag loss is included in the $(L/D)_{eq}$ parameter through the ratio S/S_0, which is also plotted in references 1 and 2 against core-structure dimensions.

Figures 3 to 6 are direct plots of reference intercooler volume against drag loss for the following operating variables:

Altitude, feet: 20,000; 30,000; 40,000; and 50,000
Dynamic pressure in flight q, inches of water: 12.5 and 25
Cooling-air pressure drop Δp_1, inches of water: 2, 6, and 10
Cooling effectiveness η, with corresponding values of M_1/M_2, percent:
η=40 percent for M_1/M_2=0.6, 0.75, 1, 1.5, and 2
η=60 percent for M_1/M_2=1.25, 1.5, 2, 3, and 5
η=80 percent for M_1/M_2=2.5, 3, 4, and 6

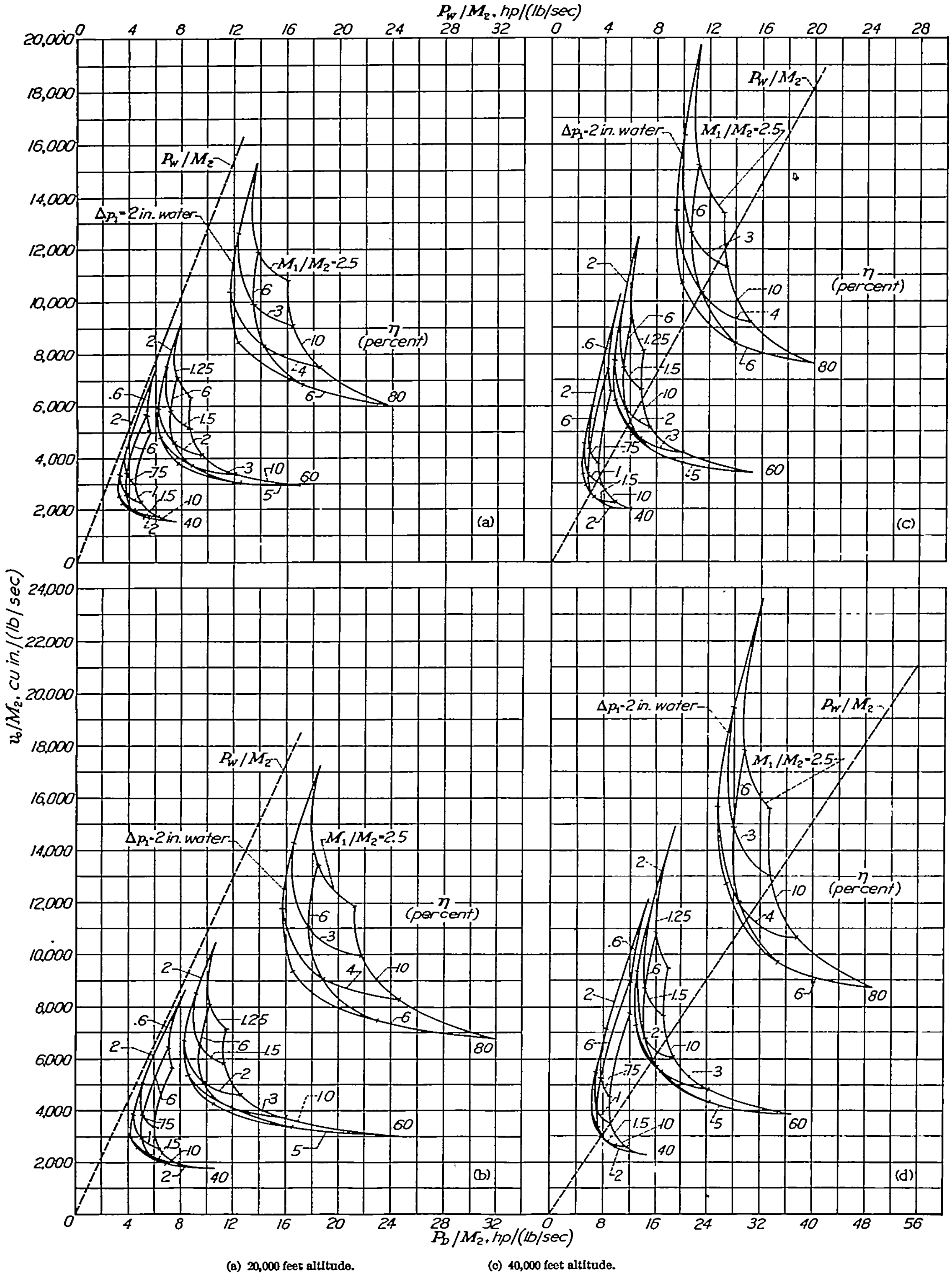
These plots are drawn for $(L/D)_{eq}=10$ and for $\sigma_{av,2}\,\Delta p_{f,2}=6$ inches of water. Included in these plots is the relation between the reference intercooler volume and the transportation drag loss expressed simply by the dashed straight line. Figures 3 and 4 apply for the plate intercooler, and figures 5 and 6 apply for the charge-through-tube intercooler.

Plots of the relation of drag loss and volume for the tubular intercoolers are the same in trend as figures 3 and 4 for the plate intercooler; the only difference is in the absolute values. Attempts were therefore made to present the relations for the tubular intercoolers in terms of correction factors for adjusting the drag loss and the volume values obtained from figures 3 and 4. For the charge-through-tube intercooler these corrections proved too complicated and involved to present; the relations for the charge-through-tube intercooler are therefore given directly in figures 5 and 6.



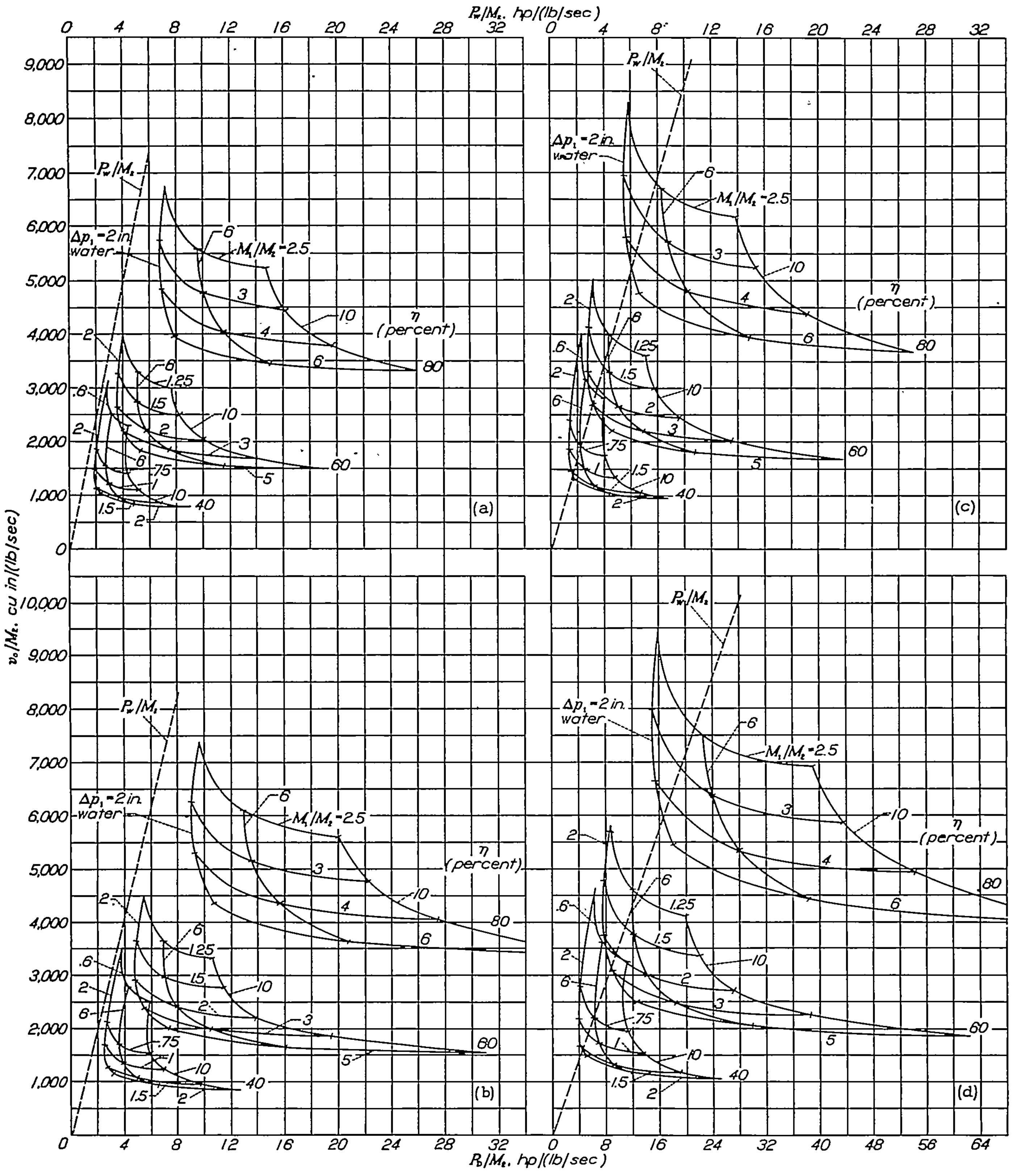
(a) 20,000 feet altitude.
(b) 30,000 feet altitude.
(c) 40,000 feet altitude.
(d) 50,000 feet altitude.

FIGURE 3.—Relation between volume and drag loss of plate intercooler when q is 12.5 inches of water. $(L/D)_{eq}$, 10; $\sigma_{a,e,2}\,\Delta p_{f,2}$, 6 inches of water.



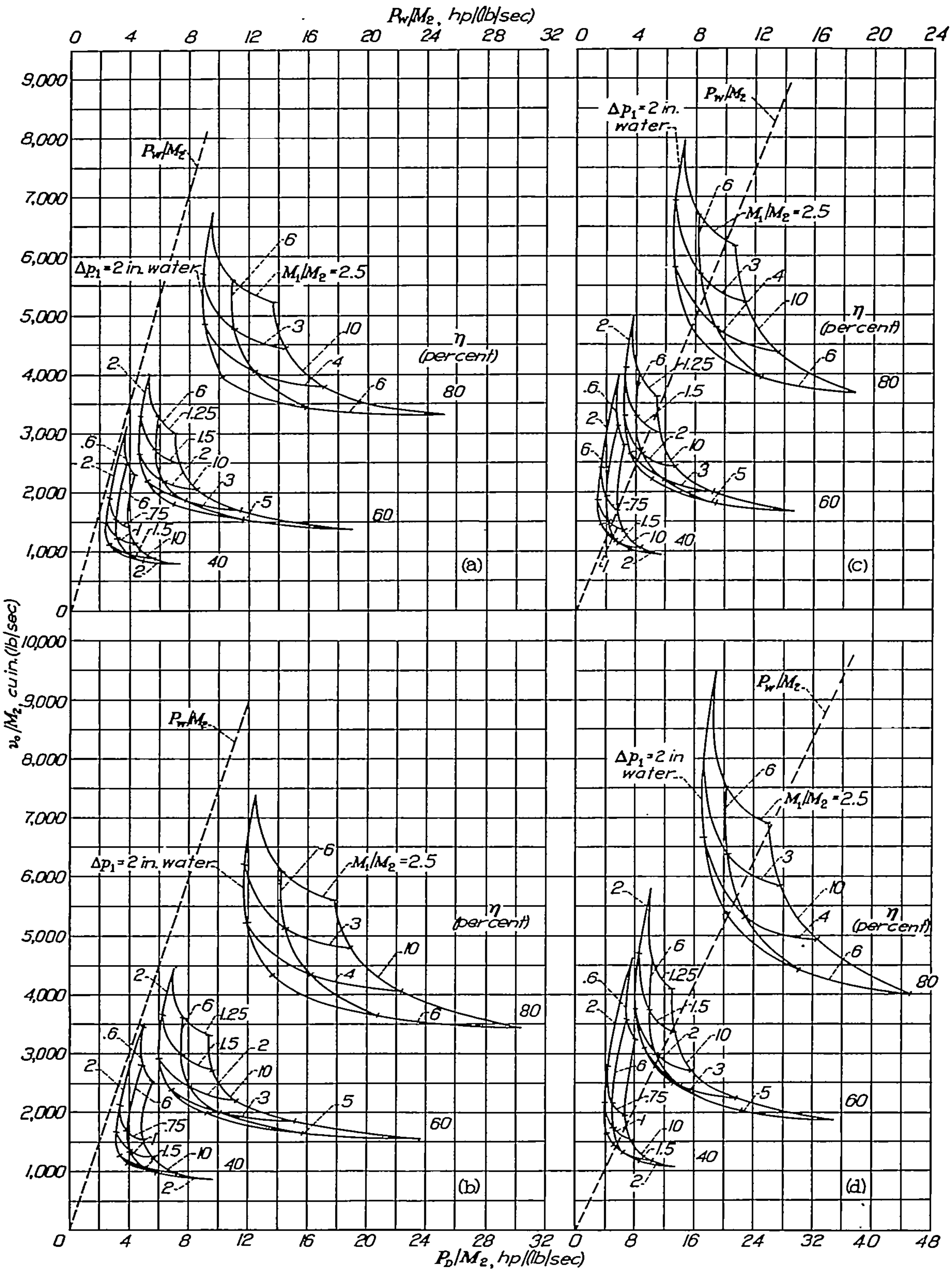
(a) 20,000 feet altitude.
(b) 30,000 feet altitude.
(c) 40,000 feet altitude.
(d) 50,000 feet altitude.

FIGURE 4.—Relation between volume and drag loss of plate intercooler when q is 25 inches of water. $(L/D)_{eq}$, 10; σ_{a_2}, 1; $\Delta p_{f,2}$, 6 inches of water.



(a) 20,000 feet altitude.
(b) 30,000 feet altitude.
(c) 40,000 feet altitude.
(d) 50,000 feet altitude.

FIGURE 5.—Relation between volume and drag loss of charge-through-tube intercooler when q is 12.5 inches of water. $(L/D)_{eq}$, 10; $\sigma_{av,2}\,\Delta p_{f,2}$, 6 inches of water.



(a) 20,000 feet altitude.
(b) 30,000 feet altitude.
(c) 40,000 feet altitude.
(d) 50,000 feet altitude.

FIGURE 6.—Relation between volume and drag loss of charge-through-tube intercooler when q is 25 inches of water. $(L/D)_{ds}$, 10; σ_{av}, 3 $\Delta p_{f,3}$, 6 inches of water.

The corrections for the charge-across-tube intercooler were found convenient to present and relatively simple to apply; these corrections are accordingly given in the form of figure 7. The ratio of the volume or transportation drag loss of the charge-across-tube intercooler to that of the plate intercooler is given in figure 7 as a function of altitude and cooling effectiveness for the same operating conditions and for $(L/D)_{eq}=10$ and $\sigma_{av,2}\ \Delta p_{f,2}=6$ inches of water. The procedure for using figure 7 in conjunction with figures 3 or 4 is summarized as follows:

1. The volume correction is directly applicable from figure 7.
2. Figures 3 or 4 can be used to find P_D/M_2, P_W/M_2, and therefore P_c/M_2, for the plate intercooler.
3. The value of P_W/M_2 can be corrected from figure 7 in the same manner as the volume.
4. For given flight and intercooler operating conditions, the cooling-air drag loss P_c/M_2 is the same for the three types of intercooler. Thus the corrected value of P_W/M_2 can be added to the unchanged value of P_c/M_2 to give P_D/M_2 for the charge-across-tube intercooler.

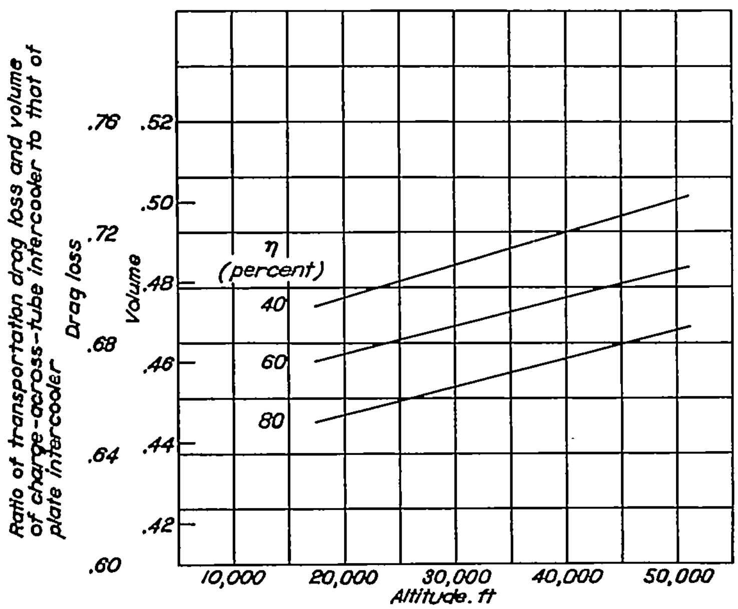


FIGURE 7.—Volume and transportation drag-loss corrections for charge-across-tube intercooler. $(L/D)_{eq}$, 10; $\sigma_{av,2}\ \Delta p_{f,2}$, 6 inches of water.

The drag loss-volume plots show that on the basis of drag loss $(M_1/M_2)_{opt}$ is not a very definite value. For example, in figure 3 (a), when $\Delta p_1=2$ inches of water and $\eta=80$ percent, little change in drag loss occurs as M_1/M_2 is varied over the entire range shown. The intercooler volume is, however, very sensitive to changes in M_1/M_2 from the optimum value. The ratio M_1/M_2 may therefore be increased quite appreciably from the optimum value with considerable reduction in intercooler volume and with only a slight increase in drag loss. These plots also show that an increase in Δp_1 from the optimum average value of 2 inches of water at a given value of M_1/M_2 causes a decrease in volume and an increase in drag loss. If as Δp_1 is increased the value of M_1/M_2 is kept optimum, the volume changes only slightly at an expense of increased drag loss. The various plots indicate the magnitude of these changes for the variety of design conditions presented.

The plots of drag loss against volume do not include values of Δp_1 below 2 inches of water. This presentation is considered unnecessary because of the rapid rise in drag loss somewhat below this value and also because of the confusion that would result in the figures. Furthermore, it is considered that the practical range of Δp_1 lies above 2 inches of water.

It is of interest to compare the curves of drag loss against volume for values of q of 12.5 and 25 inches of water in figures 3 to 6. The principal effect of increasing q (or airspeed) is an increase in drag loss at low values of Δp_1. This effect is the result of the relative magnitudes of the decrease in cooling-air drag loss and of the increase in transportation drag loss accompanying the increase in airspeed. The cooling-air-drag decrease is caused by the increased utilization of ram for thrust at the higher airspeed, that is, by the increased Meredith effect.

A value of q of 12.5 inches of water represents a good value for present-day speed of best climb; a q of 25 inches of water is typical of the high-speed condition. The analysis covering the range of q from 12.5 to 25 inches of water shows the optimum values of M_1/M_2 and Δp_1 to be independent of q.

It must be remembered that figures 3 to 7 apply only for $(L/D)_{eq}=10$ and $\sigma_{av,2}\ \Delta p_{f,2}=6$ inches of water. Further corrections for variation in $(L/D)_{eq}$ and $\sigma_{av,2}\ \Delta p_{f,2}$ are given in figures 8, 9, 10. The detailed use of these figures will be illustrated in a later section.

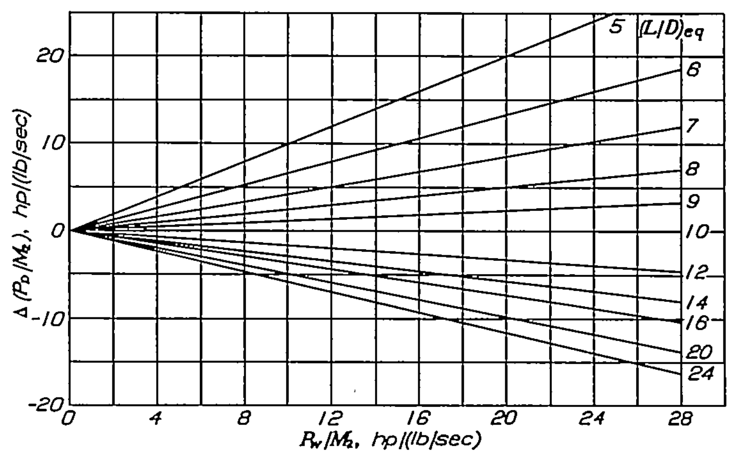
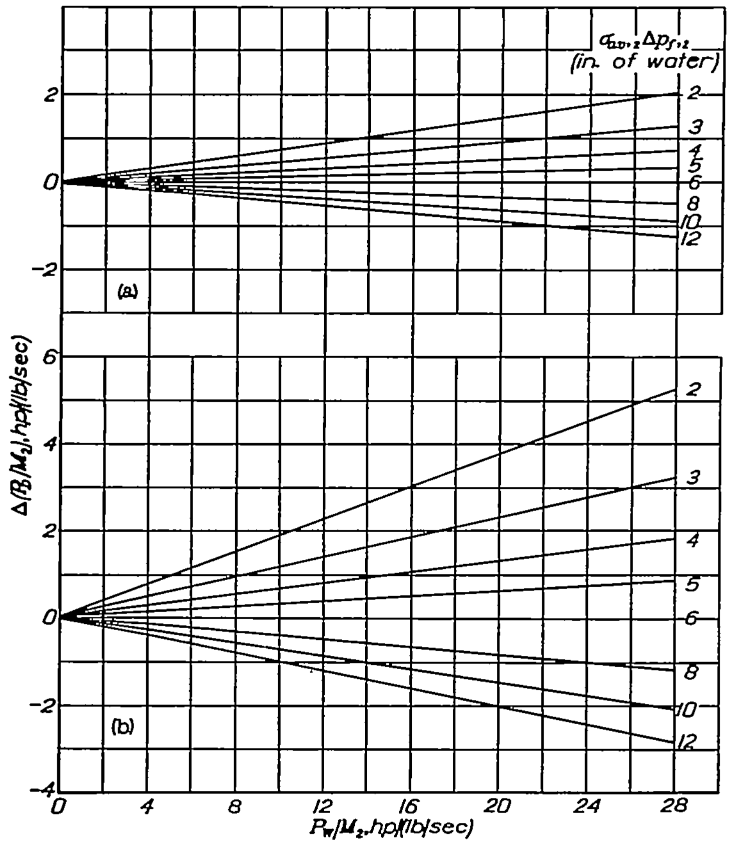


FIGURE 8.—Variation of intercooler drag loss with $(L/D)_{eq}$.



(a) Charge-across-tube intercooler.
(b) Plate and charge-through-tube intercooler.

FIGURE 9.—Corrections to intercooler drag loss for variation in charge-air pressure drop.

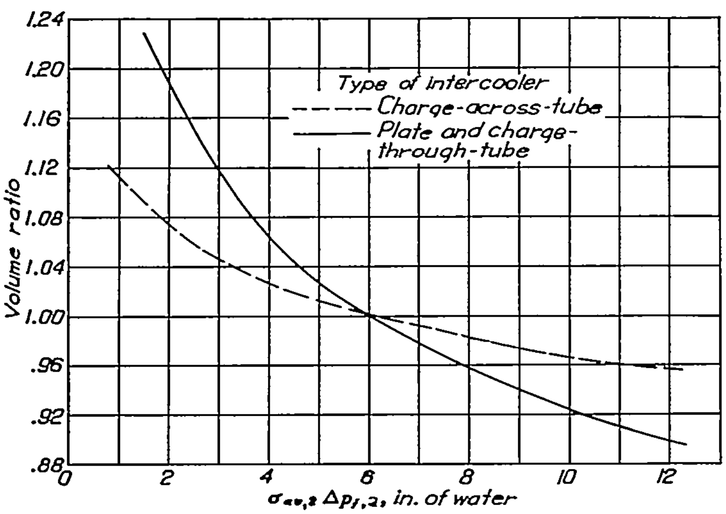


FIGURE 10.—Variation of intercooler volume with charge-air pressure drop.

Figure 9 shows that the drag loss decreases as the charge-air pressure drop increases. This effect does not mean, however, that high values of charge-air pressure drops are desirable because no account has been taken of the supercharger work required to force the charge air through the intercooler nor of the effect of charge-air pressure drop on manifold pressure. This report is confined to a study of optimum cooling-air design conditions, which for all practical purposes are independent of $\sigma_{av,2}\ \Delta p_{f,2}$ over the range covered in this report.

ILLUSTRATION OF THE USE OF THE FIGURES

Let it be required to find the volume of and the drag loss sustained by a charge-across-tube intercooler having a reference core structure (reference intercooler of reference 2) and designed to operate at the optimum cooling-air conditions. The flight and the other intercooler operating conditions are: (1) Cooling effectiveness η, 80 percent; (2) Charge-air friction loss in intercooler passages $\sigma_{av,2}\ \Delta p_{f,2}$, 10 inches of water; (3) $(L/D)_{eq}$14; (4) Altitude, 50,000 feet; (5) Dynamic pressure in flight q, 12.5 inches of water.

The outline of the procedure used in this problem is as follows:

(a) Figure 3 (d) gives the optimum cooling-air design conditions and the volume, drag loss P_D, and transportation drag loss P_W for the reference plate intercooler when $(L/D)_{eq}=10$ and $\sigma_{av,2}\ \Delta p_{f,2}=6$ inches of water.

(b) Figure 7 gives the volume and transportation drag-loss corrections applied to the values obtained for the plate intercooler to give the values for the charge-across-tube intercooler.

(c) From figure 8 the drag loss is adjusted to apply for $(L/D)_{eq}=14$. The volume is independent of $(L/D)_{eq}$.

(d) From figure 9 the drag loss is adjusted to apply for $\sigma_{av,2}\ \Delta p_{f,2}=10$ inches of water.

(e) From figure 10 the volume is adjusted to apply for $\sigma_{av,2}\ \Delta p_{f,2}=10$ inches of water.

The solution of the problem according to the foregoing outline follows.

(6) From figure 3 (d) and item (1):

$$\left(\frac{M_1}{M_2}\right)_{opt}=4 \text{ (for all practical purposes)}$$

$$(\Delta p_1)_{opt}=2 \text{ in. of water}$$

(7) Also, from figure 3 (d), for the plate intercooler:

$$v_o/M_2=15,700 \text{ cu in/(lb./sec)}$$
$$P_D/M_2=21.5 \text{ hp/(lb/sec)}$$
$$P_W/M_2=15.2 \text{ hp/(lb/sec)}$$

(8) Therefore, from item (7):

$$P_c/M_2=21.5-15.2=6.3 \text{ hp/(lb/sec)}$$

(9) From figure 7 and items (1) and (4) to correct item (7) to apply for the charge-across-tube intercooler:

$$v_o/M_2=0.468\times15,700=7340 \text{ cu in./(lb/sec)}$$
$$P_W/M_2=0.684\times15.2=10.4 \text{ hp/(lb/sec)}$$

(10) From items (8) and (9), because P_c/M_2 is independent of the type of intercooler for given flight and intercooler operating conditions:

$$P_D/M_2=6.3+10.4=16.7 \text{ hp/(lb/sec)}$$

(11) From figure 8 and item (9) the drag loss for $(L/D)_{eq}=14$ is

$$P_D/M_2=16.7-3=13.7 \text{ hp/(lb/sec)}$$

(12) From figure 9 (a) and item (11) for $\sigma_{av,2}\Delta p_{f,2}=10$ inches of water

$$P_D/M_2=13.7-0.4=13.3 \text{ hp/(lb/sec)}$$

(13) From figure 10 and item (9) for $\sigma_{av,2}\Delta p_{f,2}=10$ inches of water

$$v_o/M_2=0.97\times7340=7120 \text{ cu. in/(lb/sec)}$$

Items (12) and (13) are the final corrected values of drag loss and volume required in the problem.

It is noted that the values given for v_0 apply for the reference core structures. For a given set of intercooler operating conditions, v_0 for any other core structure may be obtained from references 1 and 2.

CONCLUSIONS

In connection with the selection of an intercooler of minimum drag and therefore maximum power-plant net gain due to charge-air cooling, the following conclusions are drawn concerning the optimum cooling conditions:

1. The optimum ratio of cooling-air weight flow to charge-air weight flow, that is, the ratio that gives minimum intercooler drag loss, is practically independent of the airplane flight conditions and the intercooler charge-air pressure drop. For all practical purposes the optimum weight-flow ratio is a simple function of the cooling effectiveness and the cooling-air pressure drop.

2. When the cooling-air weight flow is maintained at its optimum value, the cooling-air pressure drop becomes optimum between 1 and 3 inches of water regardless of the cooling effectiveness, the flight conditions, and the charge-air pressure drop. Within this range of cooling-air pressure drop there is only a slight change in drag loss from the minimum value.

3. For operation in the optimum range of cooling-air pressure drop, the optimum ratio of cooling-air weight flow to charge-air weight flow becomes a function only of cooling effectiveness.

4. For optimum cooling-air weight flow, a value of Δp_1 from 1 to 3 inches of water can be chosen without changing the drag loss an appreciable amount. There is a slight trend in favor of the lower values of Δp_1 at high altitudes. Choice of higher values of Δp_1 for a given cooling-air weight flow leads to intercoolers having larger cooling-air flow lengths and smaller no-flow dimensions than for the lower values of Δp_1. Such coolers may be more convenient to install in some cases.

5. For a given value of cooling-air pressure drop, an appreciable variation of cooling-air weight flow (within limits discussed in the report) from the optimum values will cause little change in the drag loss. An increase in cooling-air weight flow above the optimum will require an increase in the no-flow intercooler dimension, a decrease in the cooling-air flow dimension, and a decrease in intercooler volume. A reduction in cooling-air weight flow from the optimum value will reverse these trends.

6. The optimum values of cooling-air weight flow and pressure drop given herein are, within practical limits, unaffected by (1) plate or tube-wall thickness, (2) density of intercooler material, and (3) weight of accessory material required in installation. These optimum values apply equally well for the plate and tubular intercoolers.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio. *February 25, 1944.*

APPENDIX A

SYMBOLS

a ratio of cooling-air skin-friction pressure drop to total cooling-air pressure drop, $\Delta p_{f,1}/\Delta p_1$
A_r over-all effective heat-transfer area, sq ft
c_p specific heat of air at constant pressure, 0.24 Btu/(lb) (°F)
e base of natural logarithms
g acceleration of gravity, ft/sec²
L/D airplane-wing lift-drag ratio
$(L/D)_{eq}$ lift-drag ratio equivalent

$$\left[\frac{L/D}{\left(\frac{\rho_m}{173}\right)\left(\frac{12t}{0.01}\right)\left(\frac{R_W}{1.2}\right)\left(\frac{y}{2}\right)\left(\frac{S}{S_0}\right)}\right]$$

M rate of air-weight flow, lb/sec
p air pressure, in. water
Δp total pressure drop of air across intercooler, in. water
Δp_f skin-friction pressure drop of air in intercooler, in. water
P_c cooling-air drag loss, hp
P_D drag loss due to cooling air and to intercooler weight (P_c+P_W), hp
P_W drag loss expended in transportation of intercooler and its accessories, hp
q free-stream dynamic pressure, in. water
r supercharger-pressure ratio
R_W ratio of weight of intercooler to weight of intercooler plates or tubes
S heat-transfer surface area of intercooler, sq ft
t plate thickness of plate intercooler or tube-wall thickness of tubular intercooler, ft
T air temperature, °R
U over-all heat-transfer coefficient based on A_r, Btu/(sec) (sq ft) (°F)
v intercooler volume, cu ft (or cu in. where designated)
V airplane velocity, fps
W intercooler weight, lb
y ratio of increase in airplane weight caused by addition of intercooler to weight of intercooler
γ exponent of adiabatic compression
η intercooler cooling effectiveness
η_{ad} supercharger adiabatic efficiency
η_d intercooler duct efficiency
θ weight-flow pressure-drop ratio $\left(\frac{M_1\sigma_{av,1}\Delta p_{f,1}}{M_2\sigma_{av,2}\Delta p_{f,2}}\right)$
ρ air density, lb/cu ft
ρ_m density of plate or tube-wall material, lb/cu ft
σ density of air relative to standard atmosphere

Subscripts:
a free-air-stream conditions
av average conditions in intercooler
e conditions at duct exit
en conditions at intercooler entrance
ex conditions at intercooler exit
opt optimum on basis of minimum drag loss
s supercharger
o reference intercooler conditions where the reference intercooler is defined in references 1 and 2
1 cooling air
2 charge air

APPENDIX B

ANALYSIS

The application of Bernoulli's incompressible-flow equation to the cooling-air flow ahead of the intercooler (fig. 11) gives

$$p_{en}-p_a=\frac{1}{10.4g}\eta_d\rho_a(V_a^2-V_{en}^2) \tag{1}$$

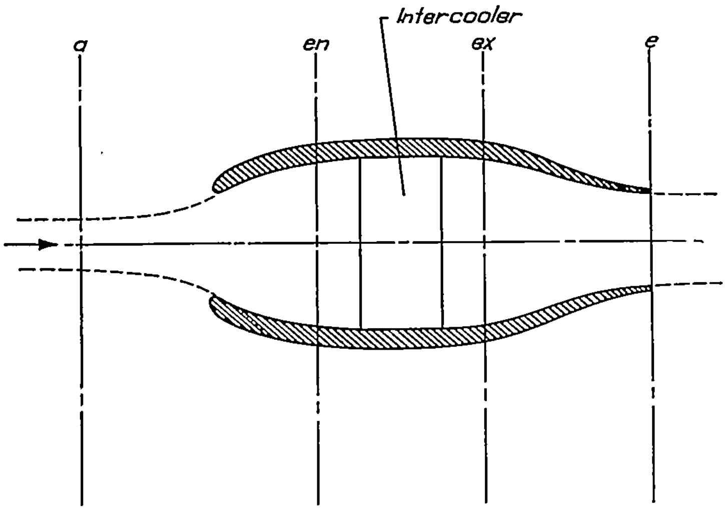


FIGURE 11.—Heat-exchanger duct system.

Also, when Bernoulli's equation is applied to the cooling-air flow behind the intercooler

$$p_{ex}-p_a=\frac{1}{10.4g}\rho_{ex}(V_e^2-V_{ex}^2) \tag{2}$$

From equation (2) the duct-exit velocity may be explicitly given as

$$V_e^2=\frac{10.4g}{\rho_{ex}}(p_{ex}-p_a)+V_{ex}^2 \tag{3}$$

The pressure drop across the intercooler may be expressed as

$$\Delta p_1=(p_{en}-p_a)-(p_{ex}-p_a) \tag{4}$$

When equations (1) and (4) are substituted in equation (3) and when the resulting equation is rearranged

$$V_e=\sqrt{\frac{\eta_d\rho_a}{\rho_{ex}}V_a^2\left[1-\left(\frac{V_{en}}{V_a}\right)^2\right]\left[1-\frac{\Delta p_1}{p_{en}-p_a}+\frac{\rho_{ex}V_{ex}^2}{\eta_d\rho_a(V_a^2-V_{en}^2)}\right]} \tag{5}$$

The cooling-air velocity near the entrance and exit faces of the intercooler is usually a very small fraction of the free-stream velocity. Thus, equation (5) may be written with negligible error as

$$V_e=V_a\sqrt{\eta_d\frac{\rho_a}{\rho_{ex}}\left(1-\frac{\Delta p_1}{p_{en}-p_a}\right)} \tag{6}$$

When the general gas law is introduced

$$\frac{\rho_a}{\rho_{ex}}=\frac{1+\frac{\Delta T_1}{T_a}}{1-\frac{\Delta p_1}{p_a}} \tag{7}$$

The cooling-air drag loss arising from the momentum change of the cooling air flowing through the duct is

$$\frac{P_c}{M_2}=\frac{M_1}{M_2}\frac{V_a}{550g}(V_a-V_e) \tag{8}$$

When equations (6) and (7) are substituted in equation (8)

$$\frac{P_c}{M_2}=\frac{M_1}{M_2}\frac{V_a^2}{550g}\left[1-\sqrt{\eta_d\left(1+\frac{\Delta T_1}{T_a}\right)\left(\frac{1-\frac{\Delta p_1}{\eta_d q}}{1-\frac{\Delta p_1}{p_a}}\right)}\right] \tag{9}$$

The ratio $\Delta T_1/T_a$ in equation (9) may be given in terms of intercooler and supercharger characteristics by the use of the heat-balance equation for the charge and cooling air. Thus,

$$\frac{\Delta T_1}{T_a}=\frac{\eta}{M_1/M_2}\frac{\Delta T_s}{T_a} \tag{10}$$

where from supercharger performance relations

$$\frac{\Delta T_s}{T_a}=\frac{r^{\frac{\gamma-1}{\gamma}}-1}{\eta_{ad}} \tag{11}$$

Transportation drag loss.—The drag loss expended in the transportation of the additional airplane weight due to the installation of an intercooler is determined on the basis of constant wing loading and thus constant take-off and landing speeds. The transportation drag loss is, then, the drag of the additional wing area required to keep constant wing loading. This drag loss is

$$\frac{P_W}{M_2}=\frac{V_a}{550\,L/D}\frac{yW}{M_2} \tag{12}$$

The relation between the intercooler heat-transfer surface area and the intercooler weight can be expressed as

$$\frac{W}{M_2}=\rho_m t R_W \frac{S}{M_2} \tag{13}$$

The foregoing equations are general and hold for both the plate and tubular intercooler. The following equations will deal specifically with the plate intercooler, although the same general procedure may also be employed with the charge-across-tube and the charge-through-tube intercoolers.

From equations (12) and (25) of reference 1 the heat-transfer surface area and the operating conditions and core-structure dimensions of the plate intercooler are related by

$$\frac{S}{M_2}=69.4\left(\frac{UA_r}{M_2c_p}\right)^{7/5}\frac{(\theta^{-2/7}+1)^{7/5}}{(\sigma_{av,2}\Delta p_{f,2})^{2/5}}\frac{S}{S_0} \tag{14}$$

where S/S_0 is a function of the core-structure dimensions and is given in reference 1 by equation (25) and figure 2.

In reference 3 the cooling effectiveness of a cross-flow plate intercooler is given as approximately

$$\eta=1-e^{-\frac{M_1}{M_2}\left(1-e^{-\frac{UA_r}{M_2c_p}\frac{M_2}{M_1}}\right)} \tag{15}$$

The solution of equation (15) for $\frac{UA_r}{M_2c_p}$ is

$$\frac{UA_r}{M_2c_p}=-\frac{M_1}{M_2}\log_e\left[\frac{\log_e(1-\eta)}{M_1/M_2}+1\right] \tag{16}$$

For convenience, define

$$(L/D)_{eq}=\frac{L/D}{\left(\frac{\rho_m}{173}\right)\left(\frac{12t}{0.01}\right)\left(\frac{R_W}{1.2}\right)\left(\frac{y}{2}\right)\left(\frac{S}{S_0}\right)} \tag{17}$$

where ρ_m, t, R_W, and y are given the reference numerical values of 173, 0.01, 1.2, and 2, respectively.

From equations (12), (13), (14), (16), and (17) the drag loss expended in transporting the plate intercooler may be given in terms of the flight and intercooler operating conditions as

$$\frac{P_W}{M_2}=\frac{-24V_a}{550(L/D)_{eq}}\left\{\frac{M_1}{M_2}\log_e\left[\frac{\log_e(1-\eta)}{M_1/M_2}+1\right]\right\}^{7/5}$$

$$\left[\left(\frac{M_1}{M_2}a\sigma_{av,1}\Delta p_1\right)^{-2/7}+(\sigma_{av,2}\Delta p_{f,2})^{-2/7}\right]^{7/5} \tag{18}$$

Solution for optimum M_1/M_2.—From equations (9), (10), (11), and (18) the drag loss can be expressed as a function of the flight and intercooler operating conditions by

$$\frac{P_D}{M_2}=K_1\frac{M_1}{M_2}\left[1-\sqrt{K_3\left(1+K_2\frac{\eta}{M_1/M_2}\right)}\right]$$

$$-K_4\left(\frac{M_1}{M_2}\right)^{7/5}\left[\left(\frac{M_1}{M_2}a\sigma_{av,1}\Delta p_1\right)^{-2/7}+(\sigma_{av,2}\Delta p_{f,2})^{-2/7}\right]^{7/5}(\log_e X)^{7/5} \tag{19}$$

where

$$K_1=\frac{V_0^2}{550g} \tag{20}$$

$$K_2=\frac{r^{(\gamma-1)/\gamma}-1}{\eta_{ad}} \tag{21}$$

$$K_3=\eta_d\left[\frac{1-\frac{\Delta p_1}{\eta_d q}}{1-\frac{\Delta p_1}{p_a}}\right] \tag{22}$$

$$K_4=\frac{24V_a}{550(L/D)_{eq}} \tag{23}$$

$$X=\frac{\log_e(1-\eta)}{M_1/M_2}+1 \tag{24}$$

The optimum value of M_1/M_2 is evaluated by first letting

$$\partial\left(\frac{P_D}{M_2}\right)\Big/\partial\left(\frac{M_1}{M_2}\right)=0 \tag{25}$$

and by then solving for M_1/M_2. The solution for M_1/M_2 in equation (25) has been obtained graphically for the following range of conditions:

η, percent	30–85
$\sigma_{av,2}\Delta p_{f,2}$, inches of water	2–12
Altitude, feet	20,000–50,000
q, inches of water	12.5–25
$(L/D)_{eq}$	5–20
r	1–3
η_{ad}, percent	65–100

The duct efficiency η_d was taken as 90 percent.

The results of the foregoing procedure can be given as

$$\left(\frac{M_1}{M_2}\right)_{opt}=\frac{be^{3.06\eta}}{\Delta p_1{}^m} \tag{26}$$

where

$$b=\phi_3\left(\frac{K_1}{K_4}K_2, K_3, \frac{\eta}{M_1/M_2}, a\sigma_{av}, 1\Delta p_1, \sigma_{av}, 2\Delta p_{f}, 2\right)$$

and

$$m=\phi_4(b)$$

Inasmuch as the terms b and m vary only slightly when minimum drag loss is the basis of design, they may for general intercooler design purposes be assumed constant at an average value for the range of flight and intercooler operating conditions covered in this report. Thus, $b=0.49$ and $m=0.36$, approximately.

Solution for optimum Δp_1.—If equation (26) is substituted in equation (19)

$$\frac{P_D}{M_2}=K_1\frac{be^{3.06\eta}}{\Delta p_1{}^m}\left[1-\sqrt{K_3\left(1+K_2\frac{\eta\Delta p_1{}^m}{be^{3.06\eta}}\right)}\right]$$

$$-K_4\left(\frac{be^{3.06\eta}}{\Delta p_1{}^m}\right)^{7/5}\left[(be^{3.06\eta}a\sigma_{av,1}\Delta p_1{}^{1-m})^{-2/7}+(\sigma_{av,2}\Delta p_{f,2})^{-2/7}\right]^{7/5}$$

$$\left\{\log_e\left[\frac{\log_e(1-\eta)\Delta p_1{}^m}{be^{3.06\eta}}+1\right]\right\}^{7/5} \tag{27}$$

The optimum value of Δp_1 when M_1/M_2 is also optimum will be defined when

$$\partial\,(P_D/M_2)/\partial\,(\Delta p_1)=0 \tag{28}$$

In this differentiation the terms b and m were considered as independent of Δp_1. This assumption was investigated over the range of values of Δp_1 between 1 and 10 inches of water and was found to be substantially true.

Graphical solutions of equation (28) for $(\Delta p_1)_{opt}$ over the range of conditions investigated in this report show that $(\Delta p_1)_{opt}$ varies between 1 and 3 inches of water.

The approximations in the foregoing analysis have been made for the purpose of simplifying the mathematics involved. The optimum cooling-air weight flow and pressure-drop values obtained through the use of these approximations have been checked against the values obtained by a more laborious method as illustrated by figures 1 and 2. The errors introduced by these approximations were found to be small and unimportant.

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