TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.



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# EFFECT OF THE REVERSAL OF AIR FLOW UPON THE DISCHARGE COEFFICIENT OF DURLEY ORIFICES.

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Marsden Ware,
Langley Memorial Aeronautical Laboratory,
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February, 1921.

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## Introduction.

In laying out apparatus for the laboratory testing of superchargers for aircraft engines at the Langley Memorial Aeronautical Laboratory, it was found most convenient to measure the air on the inlet side by drawing the air from the atmosphere through thin plate orifices at low velocities into a box and thence through a throttle into a large reservoir which in turn was in free communication with the supercharger. The orifice coefficients for this condition were unknown, as the desired type of orifice had been calibrated with the flow from the box into the atmosphere, instead of the reverse direction which would obtain with this apparatus. The present experiments were therefore undertaken in order to obtain information regarding the relationship between the coefficients for flow in the two directions.

## Method.

The apparatus used for these experiments is shown diagrammatically in Fig. 1. When the flow was from 4 to 1 (see Fig. 1), the blower maintained an air pressure of about 5" Hg. in the large tank, which was throttled into the smaller tank and led into the orifice box through a restricted passage formed by a short length of 1/2" pipe. The flow of air through the box was thus freed from the pressure pulsations that existed at the blower. Runs with the flow from 1 to 4 (see Fig. 1) were made by reversing the blower, and consequently the air direction, by reversing the direction of rotation of the driving motor.

The method followed was to take a series of observations with the flow from 4 to 1, and then to take another similar series with the direction of air flow reversed and the orifice plates inverted in their places. With each size orifice runs were made with the flow in both directions such that the pressure drops over the reference orifice, and consequently the ratios of pressures on the two sides of this orifice were very nearly identical.

By inverting the orifices when the direction of flow was reversed the effects of inaccurate orifices were eliminated, since the air always flowed through each orifice in the same relative direction. As the orifices were very carefully made, this precaution was almost superfluous, but the change was easily made and it removed all possible suspicion of error due to any irregularities in the orifices.

Considerable difficulty was experienced in securing steady air flow, and the apparatus was modified several times before a satisfactory degree of steadiness was obtained. Readings were not taken for record unless the range of oscillation of the meniscus in the undamped manometers was less than 0.4 of 1% of the head. The final data consisted of not less than four sets of readings, for each obtainable combination of the three orifice sizes with four pressure drops, in addition to a number of runs made for check purposes, making a total of over one hundred sets of readings. It is therefore believed that the field was satisfactorily covered for the range intended and that the data is truly representative.

As the ratios of pressure on the two sides of the reference orifice, and consequently the coefficients of discharge, were very nearly the same for flow in both directions, a direct means of comparison was obtained. When the flow was from 4 to 1, the amount of air passed could be computed by using known coefficients for the standard orifice. From this, the coefficients for the reference orifice could be determined. By using these reference coefficients when the flow was reversed, the coefficients for the standard orifice could be obtained for the reversed flow, a procedure which was correct because the box and baffles were symmetrical with respect to the reference orifice. However, as only the ratio between the coefficients for the standard orifice under the two conditions of flow was desired, the intermediate steps of determining the coefficients for the reference orifice were eliminated. The standard orifices used in this work were like those reported by R. J. Durley in Vol. 27 of the Transactions, American Society of Mechanical Engineers.

The following notation is used throughout the ensuing discussion:

$W$ = weight of air flowing in lbs. per sec.

$C$ = orifice discharge coefficient.

$d$ = orifice diameter in inches.

$i$ = pressure drop across orifice in inches of water.

$T$ = absolute temperature in degrees Fahrenheit.

$A$ = orifice area in sq.ft.

$K$ = ratio of specific heats, (1.406).

$Q_h$ = pressure on high side of orifice in lbs. per sq.ft.

$Q_l$ = pressure on low side of orifice in lbs. per sq.ft.

$P$ = pressure in lbs. per sq.ft.

$B$ = barometric pressure.

$D$ = density in lbs. per cu.ft.

Subscript s is used to refer to the standard orifice while r is used for the reference orifice. Primed letters are used when the flow is from 1 to 4 while unprimed letters are used for flow in the reverse direction.

For his orifice, Durley developed the formula:

$$W = C \; .6299 \; d^2 \sqrt{\frac{i}{T}}$$

For the reference orifice, use was made of the theoretical formula:

$$W = CA \sqrt{2g \frac{K}{K-1} Q_h \; D_h \left[ \left(\frac{Q_1}{Q_h}\right)^{\frac{2}{K}} - \left(\frac{Q_1}{Q_h}\right)^{\frac{K+1}{K}} \right]}$$

Then under condition of flow from 4 to 1

$$W_s = C_s \; .6299 \; (d_s)^2 \sqrt{\frac{i_s}{T_s}} \tag{1}$$

for the standard orifice, and

$$W_R = C_R \; A_R \sqrt{2g \; \frac{K}{K-1} \; P_4 \; D_4 \left[ \left(\frac{P_3}{P_4}\right)^{\frac{2}{K}} - \left(\frac{P_3}{P_4}\right)^{\frac{K+1}{K}} \right]} \tag{2}$$

for the reference orifice.

When the flow is from 1 to 4

$$W_R{}^1 = C_R{}^1 \; A_R{}^1 \sqrt{2g \; \frac{K}{K-1} \; P_3{}^1 \; D_3{}^1 \left[ \left(\frac{P_4{}^1}{P_3{}^1}\right)^{\frac{2}{K}} - \left(\frac{P_4{}^1}{P_3{}^1}\right)^{\frac{K+1}{K}} \right]} \tag{3}$$

for the reference orifice, and

$$W_s{}^1 = C_s{}^1 \; .6299 \; (d_s{}^1)^2 \sqrt{\frac{i_s{}^1}{T_s{}^1}} \tag{4}$$

for the standard orifice.

Then dividing equation (2) by equation (3)

$$\frac{W_R}{W_R{}^1} = \frac{C_R \quad A_R}{C_R{}^1 \quad A_R{}^1} \sqrt{\frac{P_4 \quad D_4 \quad \left(\frac{P_3}{P_4}\right)^{\frac{2}{K}} - \left(\frac{P_3}{P_4}\right)^{\frac{K+1}{K}}}{P_3{}^1 \quad D_3{}^1 \quad \left(\frac{P_4{}^1}{P_3{}^1}\right)^{\frac{2}{K}} - \left(\frac{P_4{}^1}{P_3{}^1}\right)^{\frac{K+1}{K}}}}$$

also by dividing equation (1) by equation (4)

$$\frac{W_s}{W_s^1} = \frac{C_s\ .6299\ (d_s)^2 \sqrt{\frac{i_s}{T_s}}}{C_s^1\ .6299\ (d_s^1)^2 \sqrt{\frac{i_s^1}{T_s^1}}}$$

and as $W_R^1 = W_s^1$; $W_R = W_s$; $A_R = A_R^1$; $d_s = d_s^1$ and $C_R$ is practically equal to $C_R^1$.

$$\frac{C_s^1}{C_s} = \sqrt{\frac{P_3^1\ D_3^1\ i_s\ T_s^1 \left[\left(\frac{P_4^1}{P_3^1}\right)^{\frac{2}{K}} - \left(\frac{P_4^1}{P_3^1}\right)^{\frac{K+1}{K}}\right]}{P_4\ D_4\ i_s^1\ T_s \left[\left(\frac{P_3}{P_4}\right)^{\frac{2}{K}} - \left(\frac{P_3}{P_4}\right)^{\frac{K+1}{K}}\right]}} \quad (5)$$

Since considerable time occasionally elapsed between corresponding runs with opposite directions of flow, differences in air densities caused by differences in air temperatures and pressures should be considered. Equation (5) takes into account temperature differences but the factor .6399 in Durley's equation is dependent upon a constant pressure of 2117 pounds per square foot. Consequently $\frac{T_s^1}{T_s}$ in equation (5) is replaced by $\frac{D_s}{D_s^1}$ in order to allow for pressure changes, giving for the final form of the ratio

$$\frac{C_s^1}{C_s} = \sqrt{\frac{P_3^1\ D_3^1\ i_s\ D_s \left[\left(\frac{P_4^1}{P_3^1}\right)^{\frac{2}{K}} - \left(\frac{P_4^1}{P_3^1}\right)^{\frac{K+1}{K}}\right]}{P_4\ D_4\ i_s^1\ D_s^1 \left[\left(\frac{P_3}{P_4}\right)^{\frac{2}{K}} - \left(\frac{P_3}{P_4}\right)^{\frac{K+1}{K}}\right]}}$$

## Description of Apparatus.

Orifices of three different diameters, 1", 1/2" and 5/16" made of aluminum plate were used. The standard orifices were burnished with plugs within .0003" of size. No plate of the standard Durley thickness (0.057") being available, the orifices were made of 1/16" plate, which was then machined to the standard thickness for a distance of about 1/2" from the orifice edge. The reference orifices were very carefully bored in 1/16" aluminum plate. Their sizes were very close to those of the standard orifices but were not accurately determined as the absolute sizes were of no consequence.

The box was made of 7/8" maple and the inside dimensions were 4" x 4", giving a ratio of box area to orifice area for the 1" orifice of somewhat over the 20:1 recommended by Durley. Rubber gaskets were placed adjacent to the orifices to ensure air tight joints when the box was pulled together by the four bolts running its entire length.

Wire screens inserted as shown on the sketch, served to diffuse the air stream discharged by the orifice and tended to make the velocity uniform across the box before the next orifice was reached.

The pressure drops were measured by alcohol manometers of a type which is sensitive to very slight pressure differences. A vertical screw carries a short inclined glass tube, one end of which is connected by rubber tubing to an alcohol reservoir. A zero reading is taken by observing the height of the tube, as indicated by a micrometer head on the screw, when the menicus in the tube coincides with a reference mark thereon. The pressure drop is determined by the difference between this reading and a reading similarly obtained after the free end of the inclined tube and the top of the reservoir are connected by rubber tubes with the points between which the drop is desired. By estimating to the tenth of a division on the micrometer head at the top of the screw, readings could be made to within .0005". However, slight fluctuations in pressure prevented such precision in the readings taken during these experiments.

The manometer connections at the box consisted of brass tubes inserted through the side of the box and flush with the inside surface. Temperatures were obtained by bare bulb mercury chemical thermometers inserted through the sides of the box well into the air body. The thermometers were graduated to 1° F.

## Results.

Fig. 2 shows the results obtained. In plotting $\frac{C_s{}^1}{C_s}$ as a function of the head across the orifice, the curves for the 1" and the 1/2" orifices are definitely determined. For the 5/16" orifice, however, the points determine a curve, shown by the dotted lines, which is not only inconsistent with both other curves but also not in accord with the natural expectation. Consequently a curve has been drawn which will best represent the points and yet be consistent with the curves for the 1/2" and 1" orifice. The limited number of check-runs possible did not appreciably alter any of the points shown for any of the curves and the reasons for the apparent inconsistency of the points for the 5/16" curve are not known.

From these curves Fig. 2 was obtained. This shows the coefficient ratio $\frac{C_S{}^1}{C_S}$ as a function of the ratio $\frac{\text{box area}}{\text{orifice area}}$.

Errors.

The equation used assumes the equality of $C_R{}^1$ and $C_R$. While this is not absolutely true, since the pressure ratio with flow in one direction is not absolutely the same as with flow in the opposite direction, the ratios were so nearly alike that it is quite probable that the ratio of $C_R{}^1$ to $C_R$ of 1:1 as used does not differ from the actual ratio by more than .034 of 1%.

The temperatures as obtained were used to determine the densities of the air inside the box, that is, $D_3{}^1$ and $D_4$ in the formula.

The thermometer readings appeared to be somewhat inconsistent, a consideration of the conditions leading to no absolutely satisfactory explanation. As the thermometers were inserted in the air stream which had some, although very little, velocity past the bulb, the readings obtained may differ slightly from the true temperature of the air, such as would be given by a thermometer moving at the same velocity as the air, due to the effects of impact and eddies. It is hardly probable, however, that this effect is very considerable, especially as there was little opportunity for the jets to impinge directly on the thermometers.

The temperature changes observed do not correspond to those of adiabatic expansion as determined by the relation $(p)^{\frac{K-1}{K}}\,T$ = constant, being very materially smaller. It is evident from this formula that the exponent of the ratio of pressure of .29 will result in temperature ratios much nearer unity than the corresponding pressure ratios. Because of this fact and because the actual temperature changes are less than those of adiabatic expansion the temperature ratios will be very much nearer unity than the pressure ratios. Since the densities enter the final equation as a ratio of the density of the air inside of the box to that outside, the temperatures and pressures which determine the densities enter as ratios and the effect of temperatures on the result will be very considerably less than the corresponding pressures.

The temperature changes observed were quite small and it is thought that any error that might result from their use is very small indeed, though a numerical estimate is difficult to obtain. In any case, the difference between temperatures corresponding to adiabatic expansion and the temperatures actually obtained would give an error in the temperatures which in the worst case would not exceed .7 of 1%. Computations of complete runs where the difference between adiabatic temperatures and the observed temperatures are greatest, result in a maximum difference of .002 in the ratio of $\frac{C_s{}^1}{C_s}$ by using first adiabatic and then observed temperatures. As the result is affected so little by using temperatures probably much greater in error than those observed it is thought that the error due to using the observed temperature readings is very small indeed. However, in the absence of a real value of the error in the temperatures, .7 of 1% has been taken as the maximum possible error, although it is highly probable that this is much larger than actually existed.

The pressure readings were in all cases correct to within less than .02" alcohol, resulting in a possible error of less than 2.0% with a 1" drop over the orifice. From considerations of the limitations of the apparatus and of the method, the maximum possible error probably does not exceed 3.2% with the 5/16" orifice at the one inch head and 2.7% with the 1" orifice at the six and one-half inch head.

Computations from the observations of the probable error of the ratio $Cs^1$ to $C_s$ result in .47% for the 1" orifice at a six and one-half inch head and .08% for the 5/16" orifice at a one inch head. It is thought that the ratios of the coefficient obtained are reliable to within less than 1%.

## Conclusions.

The results indicate that the ratio of the orifice discharge coefficient from standard orifice $C_s{}^1$ to the discharge coefficient from reverse flow $C_s$ is always less than unity, but approaches unity with increasing ratio of box area to orifice area, and that even for a ratio of areas as low as twenty the ratios of the coefficients is not much less than unity. It is probable, however, that when the ratio of box area to orifice area is much less than twenty the ratio of discharge coefficients would be greatly reduced. Since for the greater part of the range of these experiments the discharge coefficient is not reduced by more than one per cent by the reversal of flow, and the probable reliability of Durley's experiments is of about the same order, it appears that the reduction of discharge caused by reversing the direction of flow could be properly neglected in all but the most accurate testing when the ratio of box area to orifice area is greater than 20:1 and the pressure drops across the orifice is limited to 5" water.