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STEADY- AND INTERMITTENT-FLOW COEFFICIENTS OF POPPET INTAKE VALVES

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SUMMARY

Flow coefficients of an intake valve, seat, and port combination were measured under steady- and intermittent-flow conditions. Tests were conducted at large (greater than 2 in. Hg) and small (less than 2 in. Hg) pressure drops over an engine-speed range of 800 to 3600 rpm. The results of these tests indicated that (1) steady- and intermittent-flow coefficients increase slightly with increasing pressure drops across the valves, (2) the intermittent-flow coefficient is approximately equal to the average steady-flow coefficient at an engine speed of 800 rpm but decreases with increasing engine speeds above 800 rpm, and (3) the intermittent-flow coefficient decreases less with engine speed when the pressure drop across the valve is large. It is concluded that the calculated cylinder pressures based on steady-flow coefficients obtained with small pressure drops across the valve may be in error when large pressure differences exist across the valve, but that no appreciable error should be caused by using the steady-flow coefficient when the pressure difference across the valve is small.

INTRODUCTION

The effect of variation in the pressure drop on the steady-flow coefficient of poppet valves was first investigated by Lucke (reference 1), who found that the coefficients were nearly constant for all pressure drops. This result was supported by Lewis and Nutting (reference 2) and later by the authors of reference 3 who found, however, that for certain streamlined valves at low lifts the flow coefficient decreases with increasing pressure drop.

The effect of variation in the pressure drop on the flow coefficient of poppet valves under intermittent-flow conditions was also investigated in reference 1 and it was found that the intermittent-flow coefficient was not independent of the pressure drop or engine speed but no consistent variation was found. The method used in reference 1 to determine the intermittent-flow coefficient is subject to inaccuracies and, because of the method of testing, it was impossible to separate the speed and pressure-drop effects. Later tests by Waldron (reference 4) indicated that the intermittent-flow coefficient was not appreciably affected by changes in the pressure drop.

The application of steady-flow coefficients to the intermittent-flow conditions in an engine was also investigated by Lucke (reference 1) and it was concluded that the coefficients for steady and intermittent flow were not the same. The results of reference 4, however, indicated that flow coefficients obtained under steady-flow conditions can be applied to intermittent-flow conditions for engine speeds up to 2400 rpm.

The cylinder pressures during the intake and exhaust strokes can be more readily calculated if flow coefficients obtained from steady-flow tests with small pressure drops across the valve can be used. Two assumptions made in these calculations are: (1) the flow coefficient of a poppet valve does not vary with the pressure drop across the valve; and (2) the flow coefficient of a poppet valve determined under steady-flow conditions is applicable to the intermittent-flow conditions of engine operation. An investigation was conducted at the NACA Cleveland laboratory to determine the validity of these assumptions over an engine-speed range of 800 to 3600 rpm.

ANALYSIS

The steady-flow coefficient of a valve and port combination is defined by

$$C_s = M_s/M_s' \tag{1}$$

where

C_s steady-flow coefficient

M_s measured flow rate (lb/sec)

M_s' ideal flow rate (based upon the nominal area of the valve $\pi D^2/4$), (lb/sec)

The nominal area of the valve may be based on any characteristic diameter D and in this report is based on the maximum valve diameter (2.00 in.). The ideal flow rate M_s' is independent of the valve lift and, because the actual flow rate M_s varies with lift, the steady-flow coefficient C_s also varies with lift. Test data are usually presented in the form of C_s plotted against L/D curves, where L is the valve lift.

For negligible approach velocities, the ideal flow rate through the valve under steady-flow conditions for gas velocities below sonic is given by

$$M_s' = 0.491\ AP_a \sqrt{\frac{2g\gamma}{(\gamma - 1)\ RT_a}\left[\left(1 - \frac{\Delta P_v}{P_a}\right)^{\frac{2}{\gamma}} - \left(1 - \frac{\Delta P_v}{P_a}\right)^{\frac{\gamma+1}{\gamma}}\right]} \qquad (2)$$

where

A characteristic valve area, (sq in.)

P_a atmospheric pressure, (in. Hg absolute)

g gravitational acceleration, (ft/sec^2)

γ ratio of specific heats

R gas constant, (ft-lb)/(lb)($^{\circ}$R)

T_a atmospheric temperature, ($^{\circ}$R)

ΔP_v pressure drop across valve, (in. Hg)

For air γ is 1.40 and R is 53.3; therefore, equation (2) reduces to

$$M_s' = 0.793\ \frac{nD^2\ P_a}{\sqrt{T_a}} \sqrt{\left(1 - \frac{\Delta P_v}{P_a}\right)^{1.43} - \left(1 - \frac{\Delta P_v}{P_a}\right)^{1.71}} \qquad (3)$$

where n is the number of valves through which the gas flows.

When equations (1) and (3) are combined, the steady-flow coefficient becomes

$$C_s = \frac{M_s\sqrt{T_a}}{0.793nD^2\ P_a \sqrt{\left(1 - \frac{\Delta P_v}{P_a}\right)^{1.43} - \left(1 - \frac{\Delta P_v}{P_a}\right)^{1.71}}} \qquad (4)$$

Steady-flow coefficients can be plotted against valve lift, and measured values of valve lift can be plotted against crank angle. These two curves can be combined to give a curve of steady-flow coefficient against crank angle. The average steady-flow coefficient is then defined (reference 5) as the average height of this curve, or

$$C_{sa} = \frac{1}{\theta_o} \int_0^{\theta_o} C_s \, d\theta \qquad (5)$$

where

C_{sa} average steady-flow coefficient

θ any crank angle, (deg)

θ_o number of degrees during which valve is open

If steady-flow coefficients can be applied to intermittent-flow conditions, the measured air-flow rate through the valves on the test apparatus during intermittent flow should equal

$$M_i = C_{sa} M_s' \theta_o/720 \qquad (6)$$

where

M_i measured flow rate through valves under intermittent-flow conditions, (lb/sec)

$\theta_o/720$ ratio of time valves are open to total time

The intermittent-flow coefficient C_i is defined by

$$C_i = M_i/M_i' \qquad (7)$$

where M_i' is the ideal flow rate under intermittent-flow conditions in pounds per second. The ideal flow rate is given by

$$M_i' = M_s' \theta_o/720 \qquad (8)$$

When equations (6), (7), and (8) are combined, it is found that, if the steady-flow coefficients of a valve may be applied to intermittent-flow conditions,

$$C_i = C_{sa} \qquad (9)$$

In this report, the value of C_{sa} is obtained from steady-flow tests and the value of C_i is obtained from intermittent-flow tests. The values are compared and when C_i and C_{sa} are found equal, the steady-flow coefficients are applicable to intermittent-flow conditions.

APPARATUS AND TEST PROCEDURE

The apparatus used in the steady- and intermittent-flow tests is shown diagrammatically in figure 1. The left cylinder bank of an in-line engine was mounted with the lower end of cylinder 1 opening into a surge tank that had a volume of approximately 32 cubic feet. The air flow through the two intake valves of this cylinder was measured by orifices installed downstream of the surge tank according to A.S.M.E. standard practice (reference 6). The air flow from the surge tank was controlled by a throttle valve between the orifice runs and a connection to the laboratory exhaust system. A rounded approach to the intake ports reduced entrance losses of the air flowing from the atmosphere to the intake valves. The pressure drop across the valves was considered as the drop between the surge tank and the atmosphere. The exhaust-valve rocker arms were removed and the exhaust valves remained closed throughout the tests.

For the steady-flow tests, the intake-valve rocker arms were removed from cylinder 1 and the intake valves were depressed to a measured lift by the micrometer screw shown in the insert of figure 1. Air-flow rates were measured for a series of valve lifts between 0.10 and 0.60 inch and a series of pressure drops between 1 and 11 inches of mercury. Pressure drops above 4 inches of mercury were measured by a mercury-in-glass manometer and those below 4 inches of mercury were measured by a water-in-glass manometer.

For the intermittent-flow tests, the intake valves of cylinder 1 were actuated by the camshaft, which was driven by a variable-speed direct-current motor. The test procedure consisted in operating the intake valves at some fixed engine speed and measuring the air-flow rate through the valves for various pressure drops across the valves. Because of the large volume of the surge tank, the pressure drop across the valve remained essentially constant during the intermittent flow through the valves. Tests were run at a series of engine speeds between 800 and 3600 rpm and a series of pressure drops between 1 and 11 inches of mercury. High-speed valve springs were used and no incorrect valve motion was observed with a stroboscope at engine speeds up to 3600 rpm.

RESULTS

Steady-Flow Tests

The change in steady-flow coefficient with pressure drop for various values of the valve lift is given in figure 2. As shown, the flow coefficient increases with pressure drop for all valve lifts except the lowest (0.10 in.). The decrease in steady-flow coefficient with increase in pressure drop for the low valve lift of 0.10 inch is normal and similar behavior is reported in reference 3.

The change in steady-flow coefficient with lift-diameter ratio L/D is given in figure 3 for a pressure drop of 2 inches of mercury. Similar curves can be obtained for other pressure drops from the data presented in figure 2. A unity-orifice curve, also presented in figure 3, indicates the flow coefficient that would be obtained if the valve-flow coefficient, based on the actual valve-flow area at each valve lift, were unity.

In order to determine the average value of the steady-flow coefficient, the intake-valve lift was measured at various crank angles and is plotted in figure 4. From the data in figures 3 and 4, a curve of steady-flow coefficient is plotted against crank angle in figure 5. The average steady-flow coefficient C_{sa} is then obtained by measuring the average height of this curve. The average flow coefficient for a pressure drop of 2 inches of mercury is 0.322, which is indicated in figure 5. Average flow coefficients were obtained for all the pressure drops investigated and a plot of average flow coefficient against pressure drop is given in figure 6. In figure 6, the average steady-flow coefficient increases 4.7 percent with an increase in pressure drop from 1 to 11 inches of mercury for an upstream air pressure of 29.12 inches of mercury absolute.

Intermittent-Flow Tests

The change in the measured value of the intermittent-flow coefficient C_i with engine speed for various values of pressure drop is given in figure 7. The measured value of C_i was calculated by equations (3), (7), and (8) with values of M_s obtained under intermittent-flow conditions. As shown in the analysis, steady-flow coefficients C_s may be applied to intermittent-flow conditions if C_i equals C_{sa}. The comparison of C_i and C_{sa} in figure 7 indicates that, for engine speeds below 800 rpm, the average and the intermittent-flow coefficients are probably equal but that, for engine speeds above 800 rpm, the intermittent-flow coefficient C_i is less than the average steady-flow coefficient C_{sa}. Figure 7 also indicates that, for high engine speeds, the difference between C_i and C_{sa} is greater for the lower pressure drops across the valve. For example, at an engine speed of 3600 rpm, C_i is approximately 91 percent of C_{sa} when the pressure drop across the valve is 1 inch of mercury; when the pressure drop is 11 inches of mercury, however, C_i is approximately 98 percent of C_{sa}.

The intermittent-flow-coeffient curves of figure 7 are combined in a single plot given in figure 8. In this figure it will be noted that the intermittent-flow coefficient C_i increases with increase in pressure drop and decreases with increase in engine speed. The maximum value of C_i (engine speed, 800 rpm; pressure drop, 11 in. Hg) is approximately 14.5 percent greater than the minimum value of C_i (engine speed, 3600 rpm; pressure drop, 1 in. Hg).

DISCUSSION

If steady-flow coefficients obtained with small (less than 2 in. Hg) pressure drops across the valve are used to calculate cylinder pressures during the intake and exhaust strokes, the results of these tests indicate that the calculations may be in error when the pressure drop across the valve is large (greater than 2 in. Hg) or when the pressure drop is small and the engine speed is high. In both cases the error will be a small percentage of the pressure drop. Therefore, for large pressure drops the error in absolute value of the cylinder pressure may be appreciable but for small pressure drops the error will be negligible, provided that sufficient time has elapsed to eliminate errors introduced by the large pressure drops previously existing across the valve (such as occur during the exhaust stroke).

In order to apply the results of these tests to engine conditions, the instantaneous value of the intermittent-flow coefficient is assumed to vary with pressure drop and engine speed in the same manner as the average value of the intermittent-flow coefficient. It is also assumed that the instantaneous value of the intermittent-flow coefficient depends upon the instantaneous pressure drop across the valve and is independent of the rate of change of pressure drop.

From the results of these tests, it is concluded that the flow coefficient of a poppet valve increases slightly with the pressure drop across the valve except at very low valve lifts and that the accuracy of cylinder-pressure calculations might be increased if this phenomenon is taken into consideration. It is also concluded that steady-flow coefficients obtained with low pressure drops across the valve can be applied to the intermittent-flow conditions in an engine with no appreciable error except perhaps when the pressure drop across the valve is large or when the pressure drop is small but sufficient time has not elapsed to eliminate errors introduced when large pressure drops previously existed across the valve.

SUMMARY OF RESULTS

From an investigation of the steady- and intermittent-flow coefficients of poppet intake valves of a conventional in-line engine over a range of pressure drops between 1 and 11 inches of mercury and a range of engine speeds between 800 and 3600 rpm, the following results were obtained:

1. The steady-flow coefficient increased slightly with pressure drop for all valve lifts except the lowest (0.10 in.) at which lift the coefficient decreased with increasing pressure drop.

2. The average steady-flow coefficient increased 4.7 percent with an increase in pressure drop from 1 to 11 inches of mercury for an inlet pressure of 29.12 inches of mercury absolute.

3. Trends in the test data indicate that the average steady-flow coefficient and the intermittent-flow coefficient were approximately equal for engine speeds below 800 rpm. The intermittent-flow coefficient became progressively less than the steady-flow coefficient as the engine speed increased above 800 rpm.

4. The difference between the average steady-flow coefficient and the intermittent-flow coefficient at high engine speeds was larger for the low pressure drops. For the largest pressure drop (11 in. Hg at an inlet pressure of 29.12 in. Hg absolute) the intermittent-flow coefficient was only slightly lower than the average steady-flow coefficient.

CONCLUSIONS

From an analysis of the results of these tests, it is concluded that:

1. The steady-flow coefficients obtained with low pressure drops across the valve can be applied to the intermittent-flow conditions in an engine with no appreciable error in the absolute value of the

calculated cylinder pressure except when the pressure drop across the valve is large or when the pressure drop is small but sufficient time has not elapsed to eliminate errors introduced when large pressure drops previously existed across the valve.

2. The accuracy of cylinder-pressure calculations might be improved if the increase in the flow coefficient with increased pressure drop across the valve is taken into consideration.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 14, 1946.

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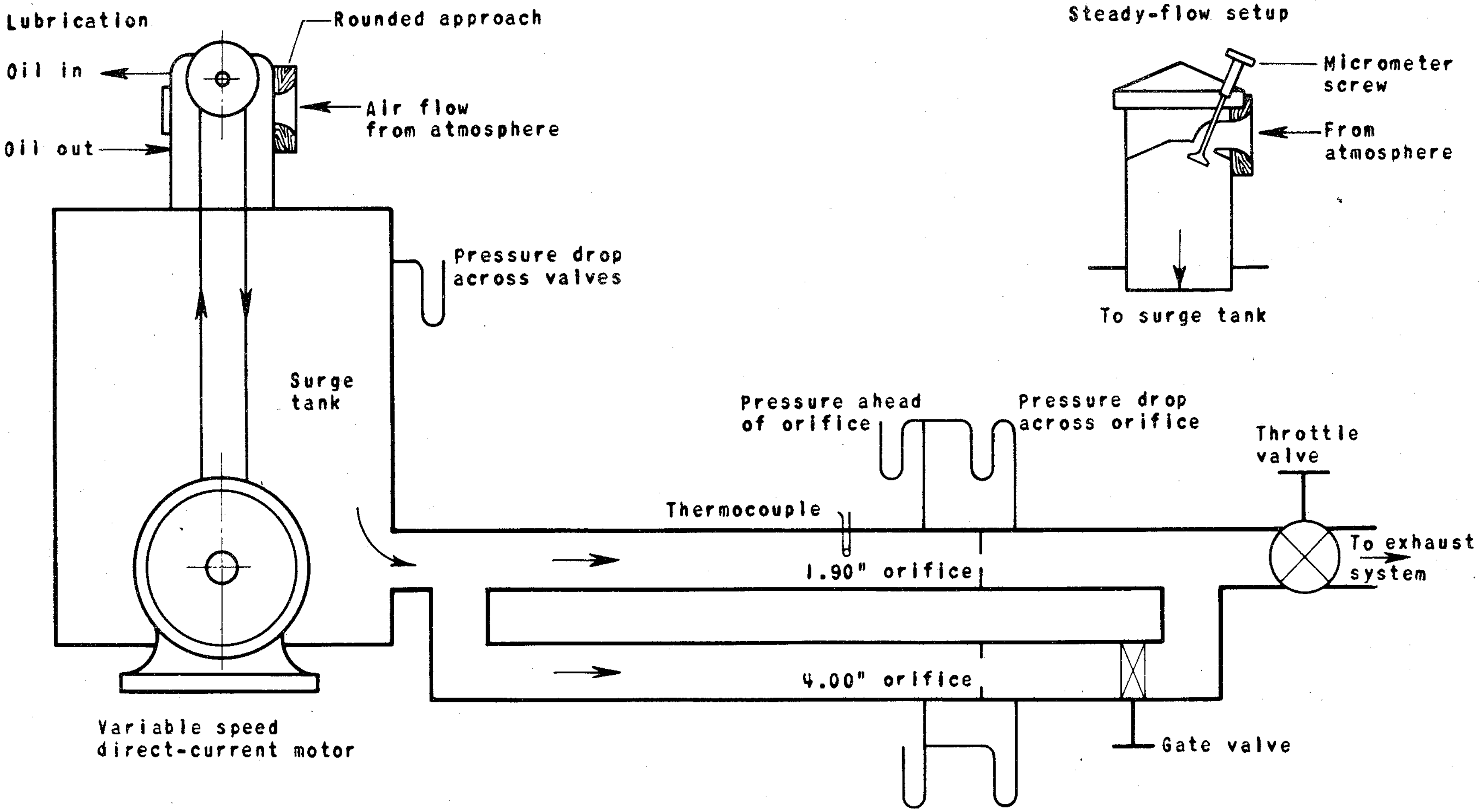

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Figure 1. - Diagrammatic sketch of apparatus for steady- and intermittent-flow tests.

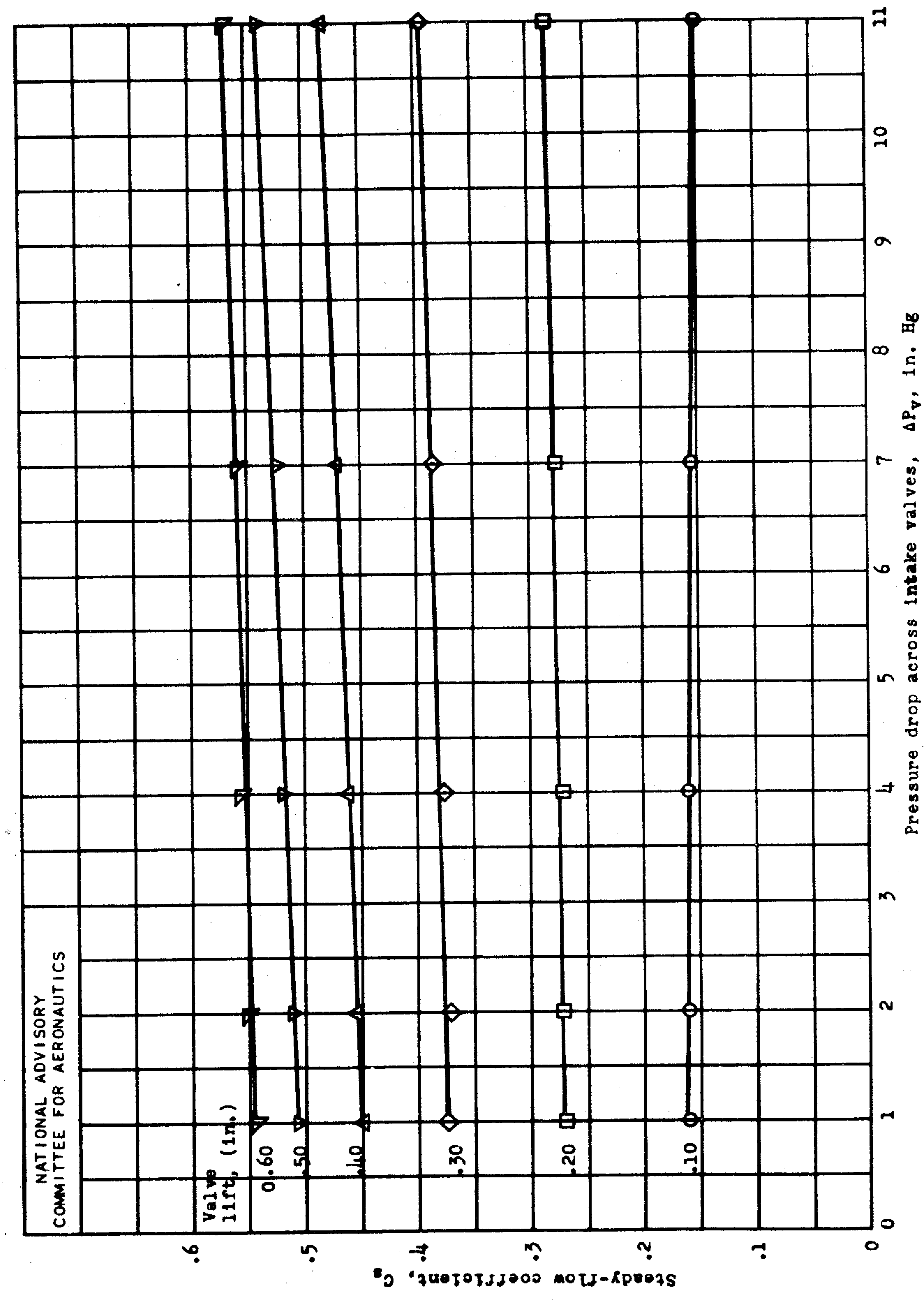

Figure 2. - Change in steady-flow coefficient with pressure drop across the intake valves. Upstream air pressure, 29.12 inches mercury absolute; valve diameter, 2.00 inches.

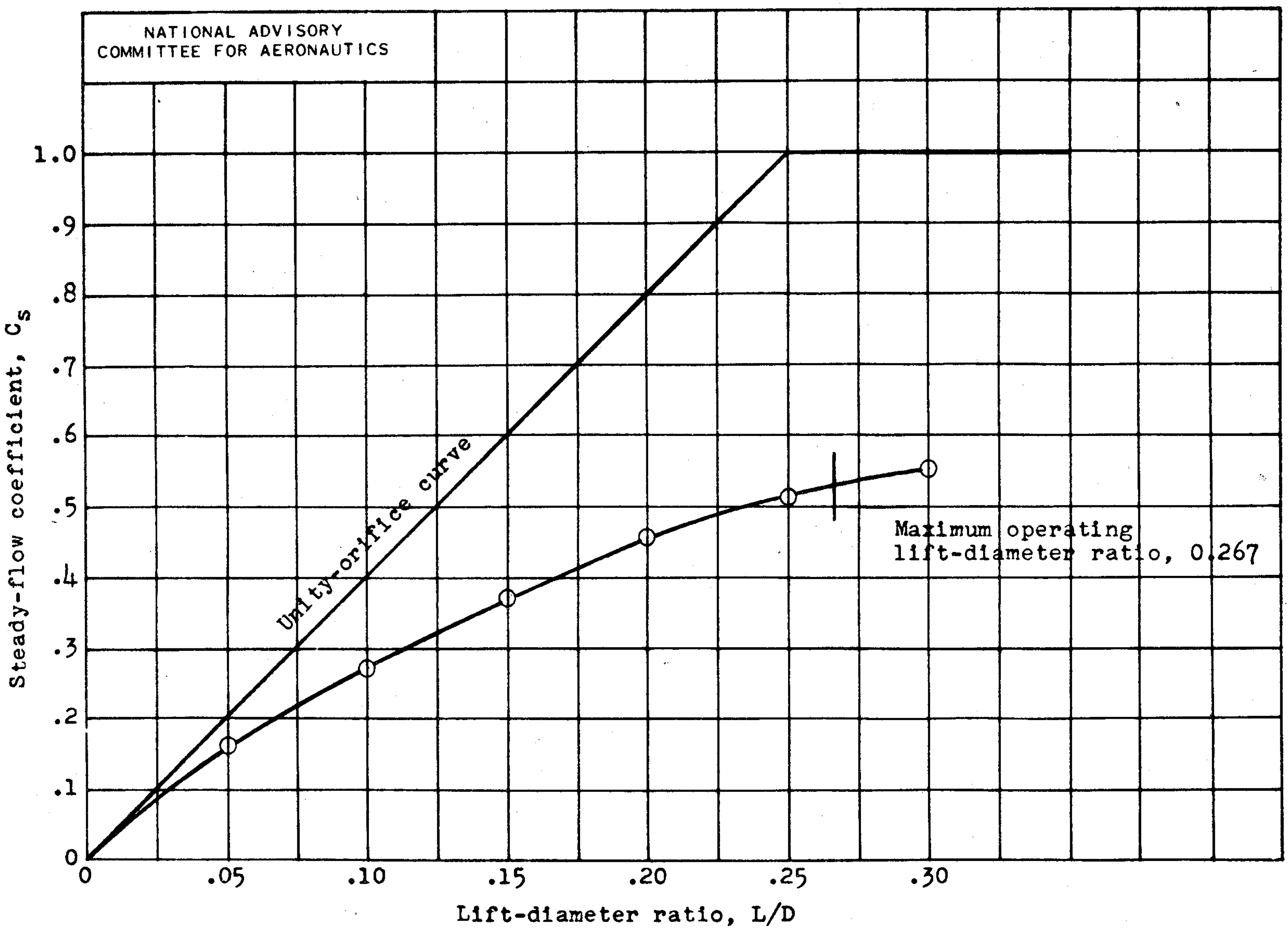

Figure 3. - Change in steady-flow coefficient with intake-valve lift-diameter ratio. Pressure drop across valve, 2.00 inches mercury; upstream air pressure, 29.12 inches mercury absolute; valve diameter, 2.00 inches.

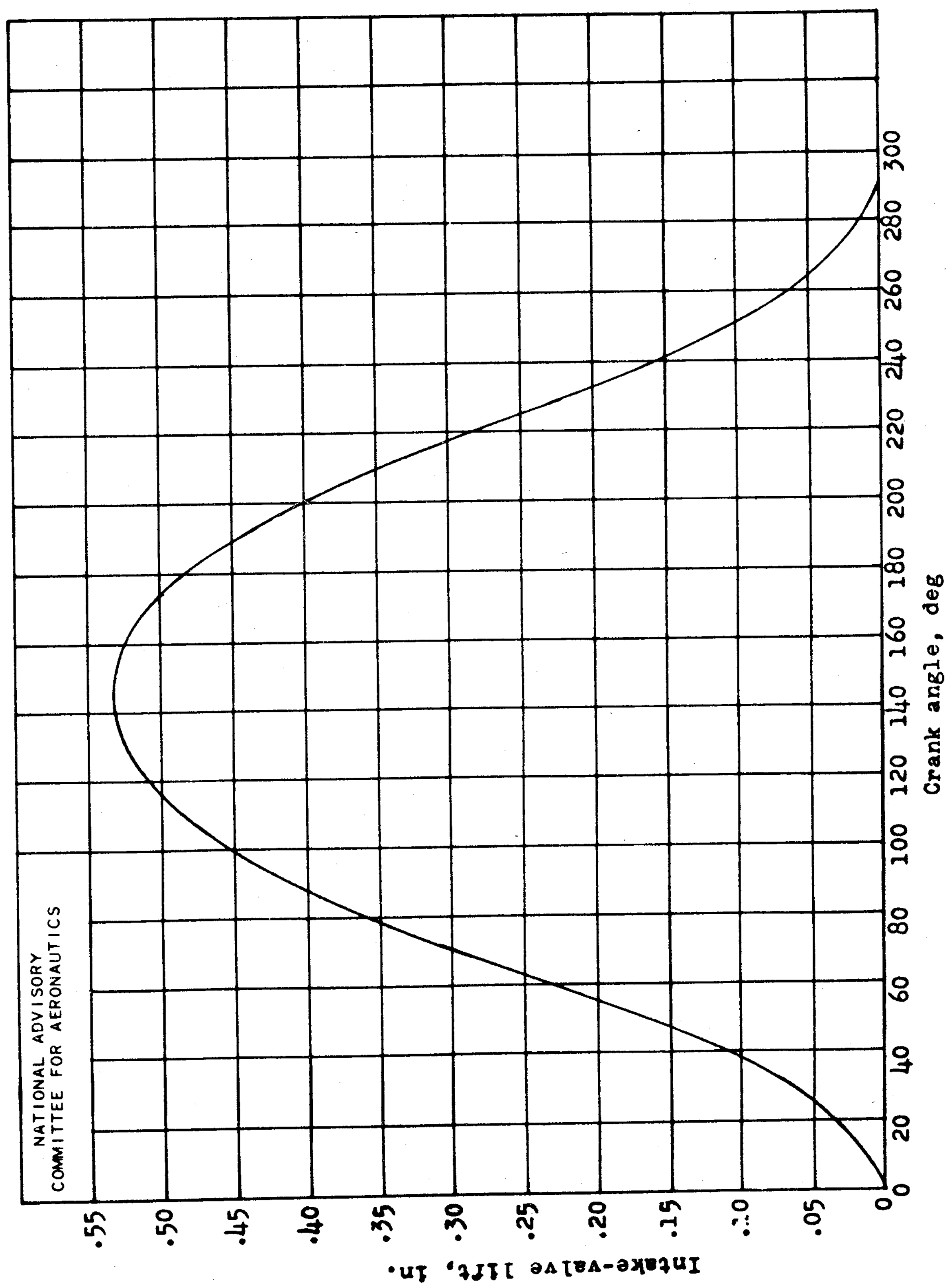

Figure 4. - Measured intake-valve lift curve.

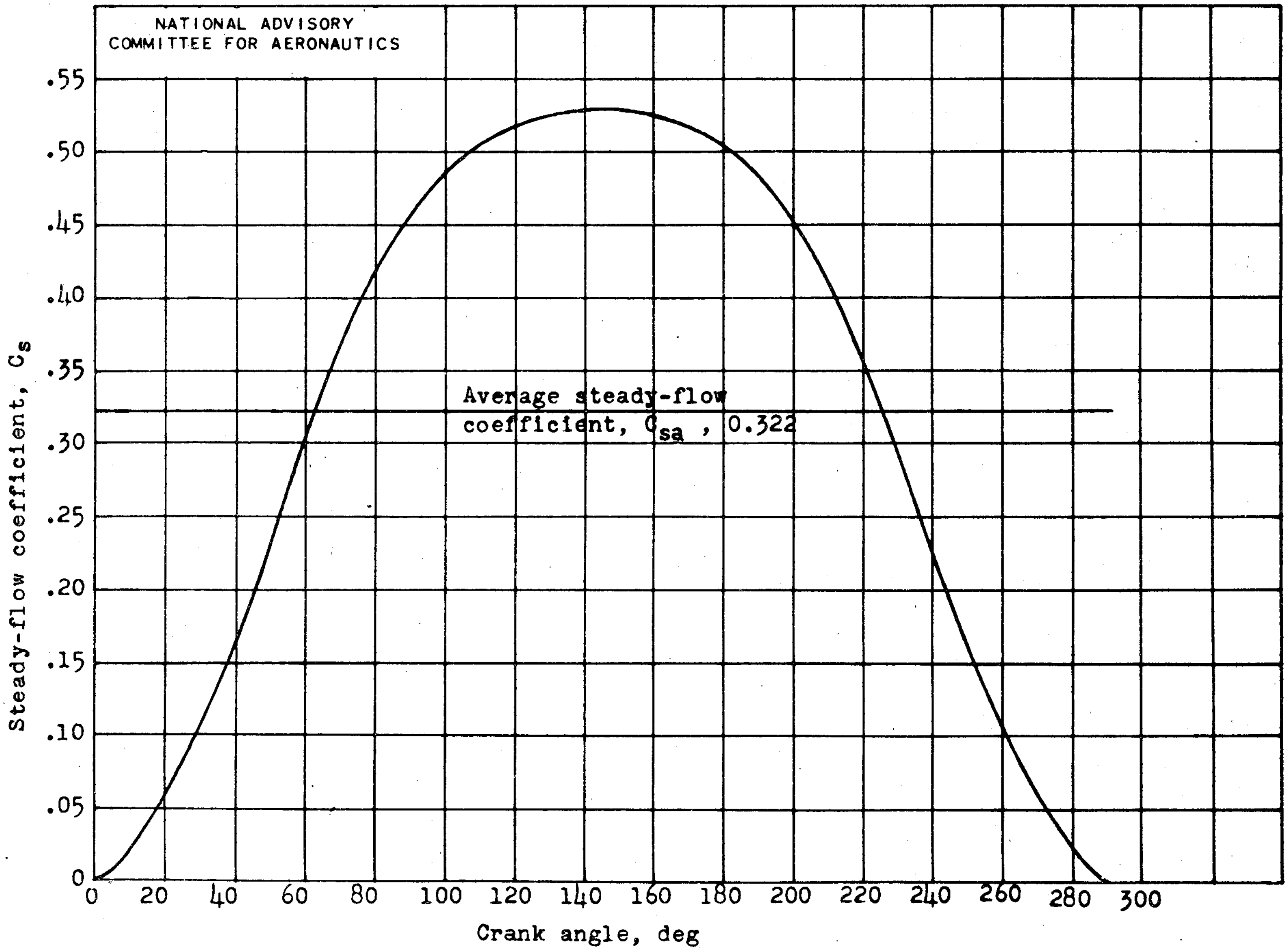

Figure 5. - Change in steady-flow coefficient C_s of intake valve with crank angle. Pressure drop across valve, 2.00 inches mercury; upstream air pressure, 29.12 inches mercury absolute; valve diameter, 2.00 inches.

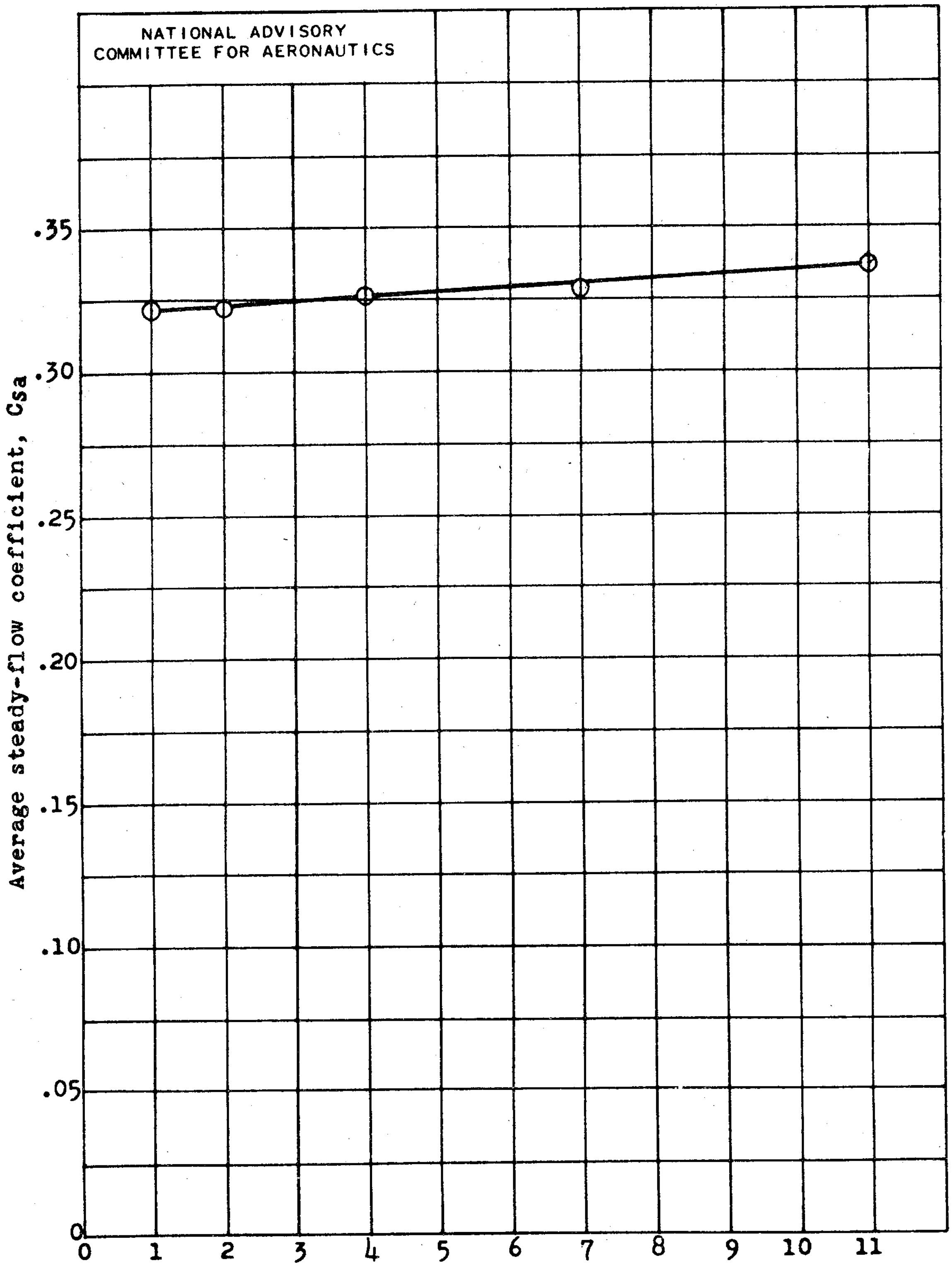

Figure 6. - Change in average steady-flow coefficient. C_{sa} with pressure drop. Upstream air pressure, 29.12 inches mercury absolute; valve diameter, 2.00 inches.

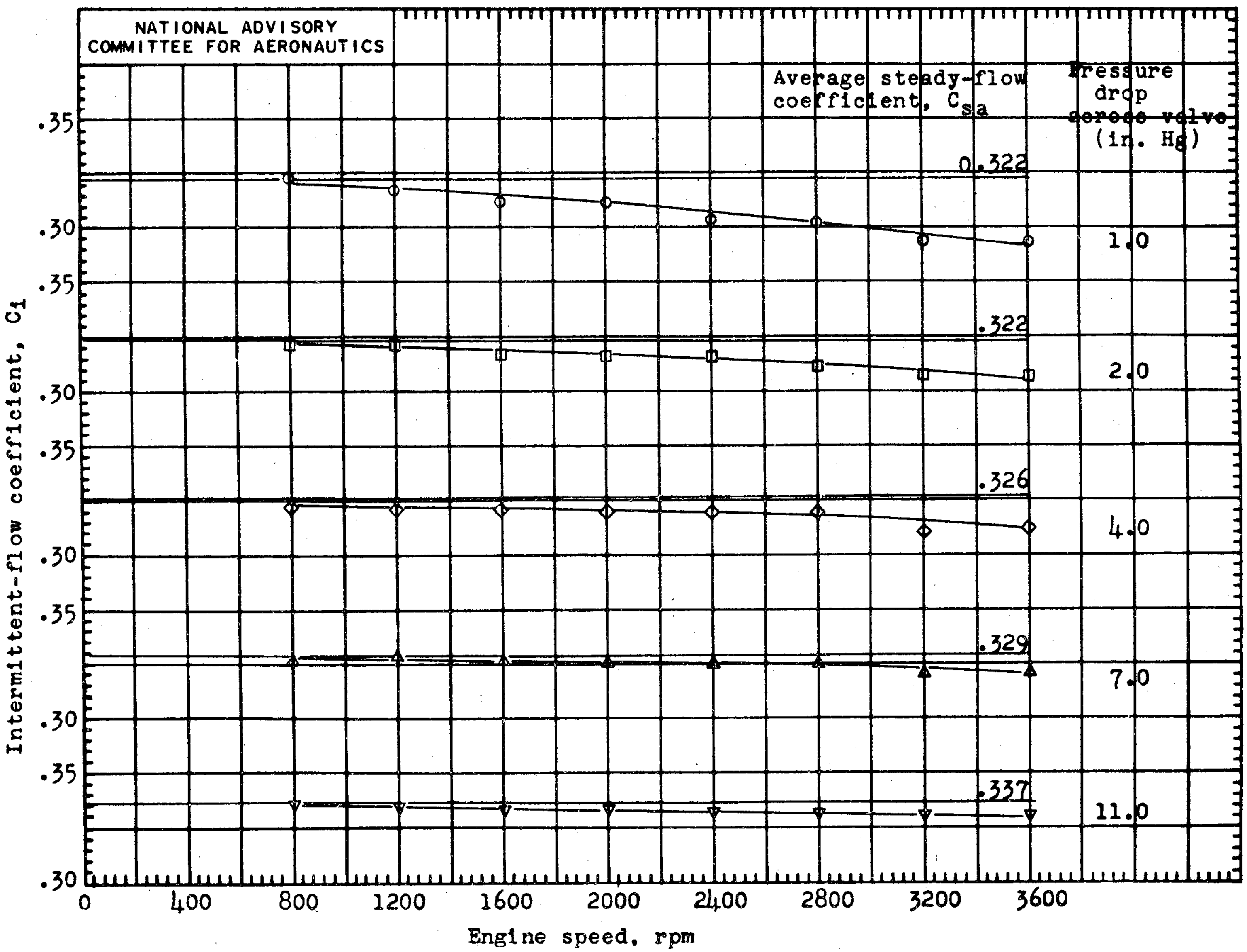

Figure 7. - Change in intermittent-flow coefficient C_i with engine speed for various pressure drops across intake valve. Upstream air pressure, 29.07 inches mercury absolute; valve diameter, 2.00 inches.

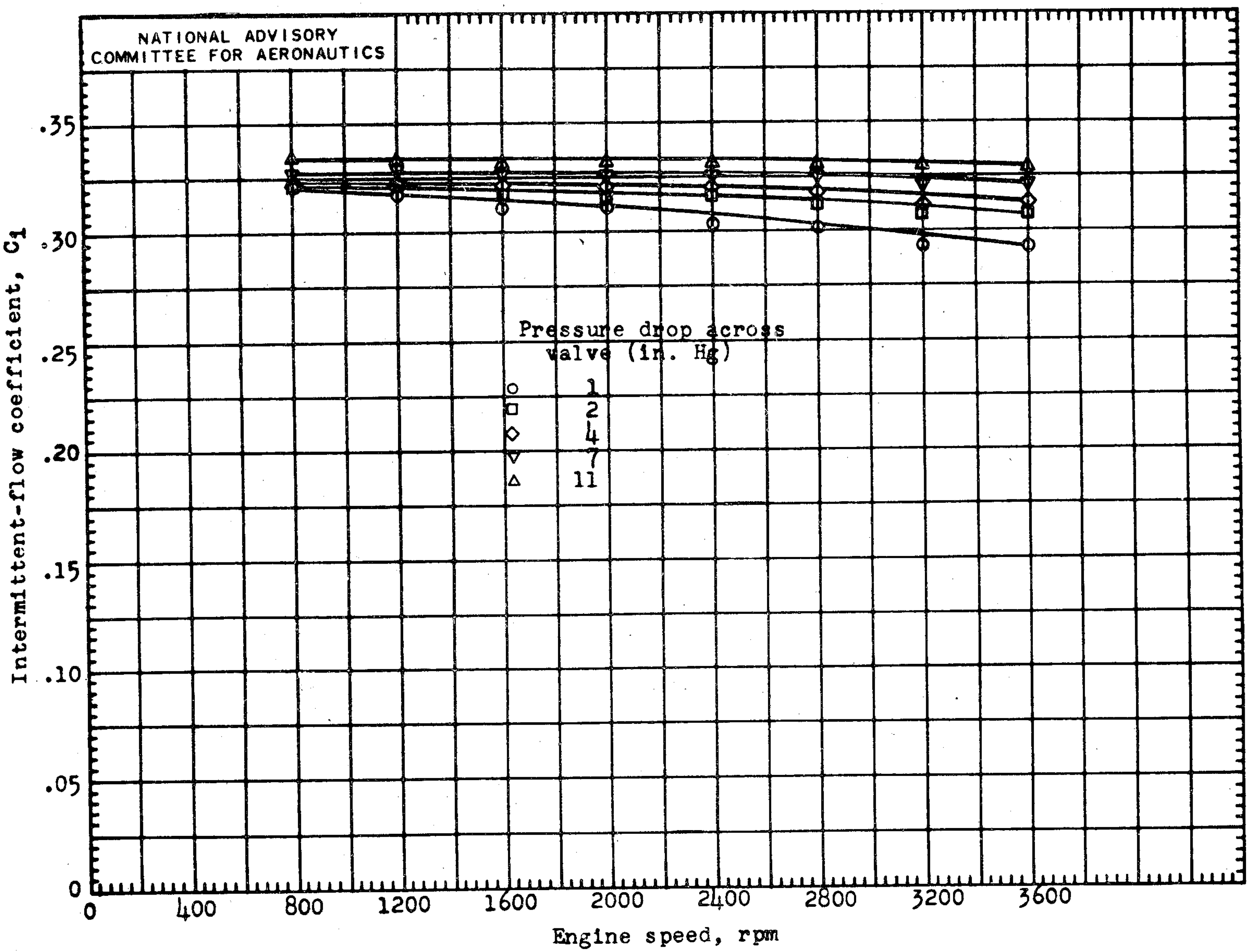

Figure 8. - Change in intermittent-flow coefficient C_i with engine speed and pressure drop across valve. Upstream air pressure, 29.07 inches mercury absolute; valve diameter, 2.00 inches.