NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 714

AN APPARATUS FOR MEASURING RATES OF DISCHARGE OF A FUEL-INJECTION SYSTEM

By FRANCIS J. DUTEE

1941

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)	----------	horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight$=mg$

g Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass$=\frac{W}{g}$

I Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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Langley Memorial Aeronautical Laboratory

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 714

AN APPARATUS FOR MEASURING RATES OF DISCHARGE OF A FUEL-INJECTION SYSTEM

By Francis J. Dutee

SUMMARY

A portable apparatus for rapidly determining rates of discharge of a fuel-injection system is described. Satisfactory operation of this apparatus with injection-pump speeds up to 2400 rpm was obtained. Rate-of-discharge tests were made with several cam-plunger-valve injection systems with long injection tubes. A check valve designed to reduce secondary discharges was tested. This check valve was operated with injection-pump speeds up to 2400 rpm without the occurrence of large secondary discharges.

Comparable performance tests on the two-stroke-cycle compression-ignition engine were made with low fuel-injection rate and with the highest injection rate obtained. The maximum gross brake mean effective pressure was increased 7.6 percent, and the minimum gross brake specific fuel consumption was decreased 6.2 percent by changing from the lower to the higher injection rate.

INTRODUCTION

Experimental work on the effect of fuel-injection characteristics upon the performance of compression-ignition engines has in the past been limited principally to consideration of the injection period. Data in reference 1 show that a short injection period is desirable from considerations of power output and fuel economy. A knowledge of the quantitative rate of discharge for all conditions of operation of the injection system is needed in order that the effects of the rate of injection on engine performance may be fully investigated.

Injection systems that have long discharge periods accompanied by large secondary injections are undesirable because they result in late burning, smoky exhaust, and a relatively high specific fuel consumption. These injection characteristics occur at high engine speeds or high throttle settings.

Apparatus that have been used for the determination of injection characteristics include: injection-valve-stem lift indicators, pressure indicators of the cathode-ray oscillograph type, and the slotted-disk type of rate-of-discharge apparatus described in reference 2. References 2 and 3 show the rate-of-discharge characteristics of some cam-plunger-valve injection systems using long injection tubes for pump speeds up to 1000 rpm.

An apparatus that gives a quick and an accurate measurement of the rate of discharge has been designed by the NACA and is described in this report. Mr. George T. Hemmeter, formerly on the Committee staff, aided in the conception and the preliminary design of the apparatus. Rate-of-discharge data are included to show the reproducibility of test results. A pump check valve that reduces secondary discharges was tested with two different cam outlines and with pump speeds from 1250 to 2400 rpm. The performance data obtained with this check valve are presented together with comparable data obtained with a Bosch check valve. Some data are included to show the effect of rate of injection upon the performance of a two-stroke-cycle compression-ignition engine at a speed of 1800 rpm. The work was done in 1937 and 1939 at Langley Field, Va.

APPARATUS

RATE-OF-DISCHARGE APPARATUS

Description.—The rate-of-discharge apparatus used in these tests is a portable unit designed for use in conjunction with the NACA universal test engine and an electric dynamometer. It consists essentially of a high-speed rotary fuel receiver and an adjustable mounting bracket for the injection valve. During rate-of-discharge tests, the engine is motored by means of the electric dynamometer. Figure 1 is a photograph of the apparatus connected to the test engine and the injection pump. The rotor is gear-driven by a power take-off from the water-pump shaft of the test engine. It is designed for safe operation with a maximum engine crankshaft speed of 3000 rpm (rotor speed of 5000 rpm) and injection pump speeds of 1500 and 3000 rpm on four- and two-stroke-cycle engines, respectively.

Seventy receiver compartments extend around the upper periphery of the rotor shown in figure 2. These compartments are connected by drilled fuel passageways to glass tubes that serve as fuel reservoirs. Each glass tube has an internal capacity of 0.390 cubic inch and is graduated in increments of 0.003 cubic inch. These tubes are mounted in retaining grooves milled in the periphery of the forged aluminum-alloy rotor. The calibration markings on the tubes are exposed to view through slots in the outer circumference of the rotor.

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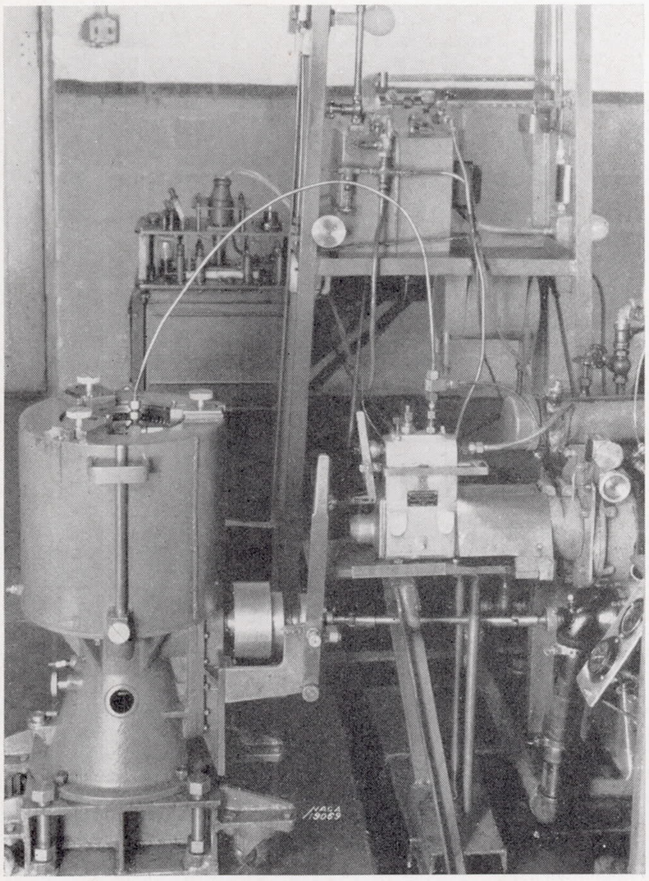


FIGURE 1.—Rate-of-discharge apparatus and test equipment.

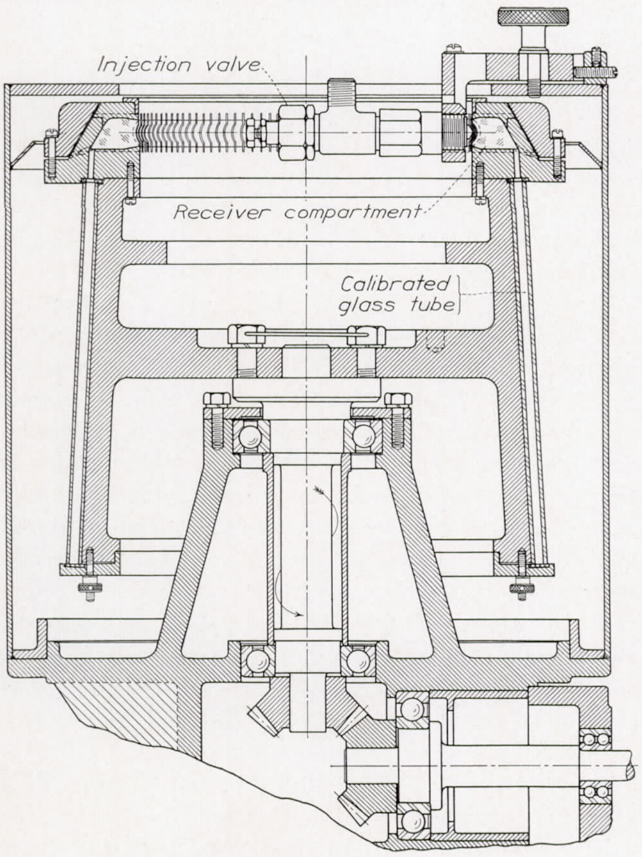


FIGURE 2.—Rate-of-discharge apparatus, sectional diagram.

The sides of each receiver are formed by two vanes so spaced that the receiver will collect fuel during a 1° rotation of the engine crankshaft. The centers of adjacent receivers have an angular spacing about the center of the rotor of 5°, equivalent to a 3° rotation of the engine crankshaft. The receiver compartments are divided into three sections, two of which contain 23 receivers and one which contains 24 receivers. These sections are separated from each other by three equal spacings on the circumference of such a width that angular rotation of the rotor between centers of adjacent receivers is 8°20′, which is equivalent to a 5° rotation of the engine crankshaft. One of these spacings is shown at A in figure 3.

During operation the fuel is discharged from the injection valve, is collected in the receivers, and is transmitted by centrifugal force into the glass tubes. Fuel that is discharged between the receivers is wasted. After a test run the volume of fuel collected in each tube can be quickly observed and recorded.

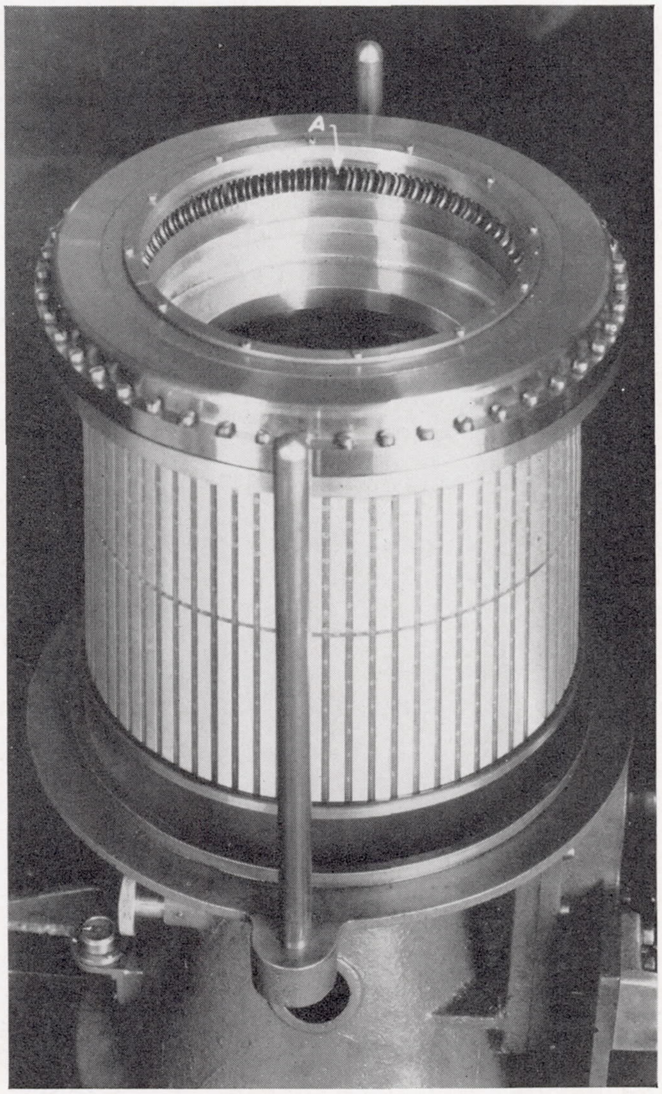


FIGURE 3.—Rotor assembly, view showing vanes and receiver compartments.

At the beginning of each test run the injection start is synchronized with the receiver sections by means of a Stroborama in such a manner that any single discharge is completed within a single section of receivers. Successive discharges occur alternately within the three sections owing to the fact that the rotor revolves at a speed 1⅔ times the speed of the engine crankshaft. The receiver compartments of any section are 1° out of phase with the compartments of either of the other two sections. Each section provides data for rate of discharge to define the curve every 3° of the engine crankshaft, and the data from the three sections can be correlated to define the curve every 1°. Each section of receivers collects approximately the same weight of fuel, and thus satisfactory balance of the rotor is maintained throughout the test run.

The rotor may be started and stopped by a friction clutch provided in the apparatus. This clutch includes a positive engagement mechanism by which the angular position of the rotor can be adjusted and locked in the proper phase relation with the injection-pump shaft.

Operation.—The amount of fuel discharged during each test run was adjusted to such a value that the maximum quantity of fuel collected by any one of the glass tubes filled the tube within the limits of 70 to 100 percent of its capacity. The number of fuel discharges during each test run was thus necessarily varied approximately inversely with the maximum rate of discharge of the injection system. In figure 4, for example, each curve represents an average of at least 1640 discharges. A fuel scale that automatically weighed a predetermined amount of fuel controlled a solenoid-operated stop watch and revolution counter. The injection-pump throttle was manually opened at the beginning of each test run and closed at the end of each test run. The apparatus operated satisfactorily at the highest test speed of 2400 rpm. Operation at higher speeds appeared feasible. No difficulty was experienced from vibration originating within the apparatus.

After the test equipment had been completely assembled, a test run for any one condition of speed and throttle setting could be made in 8 minutes. This operation included starting, synchronizing, operating the injection system, stopping, recording data, and draining and sealing the glass tubes for another test run.

Reproducibility and accuracy.—A large number of preliminary rate-of-discharge tests were made with the apparatus to calibrate the equipment and develop a satisfactory method of operation. Figure 4 shows the reproducibility obtained in four sets of rate-of-discharge data taken with comparable injection-system conditions. In 44 rate-of-discharge tests with various conditions of pump speed and throttle setting, the greatest discrepancy between the average fuel quantity per injection as determined by the rate-of-discharge apparatus and as determined by the fuel scale was 4 percent. No error could be detected in the period of discharge as indicated by the rate-of-discharge apparatus from observation of the fuel sprays with the aid of a Stroborama.

The best results were obtained with the apparatus when injection nozzles having all orifices in a single vertical plane were used. The operating clearance between the injection nozzle and the edge of the receiver vanes was found to have no effect on the accuracy of the rate-of-discharge data for clearances less than 0.060 inch. A clearance of 0.050 inch was used in these tests. Tests with an injection valve delivering a cone-type spray indicated some sacrifice in accuracy because the tip of the valve was so shaped

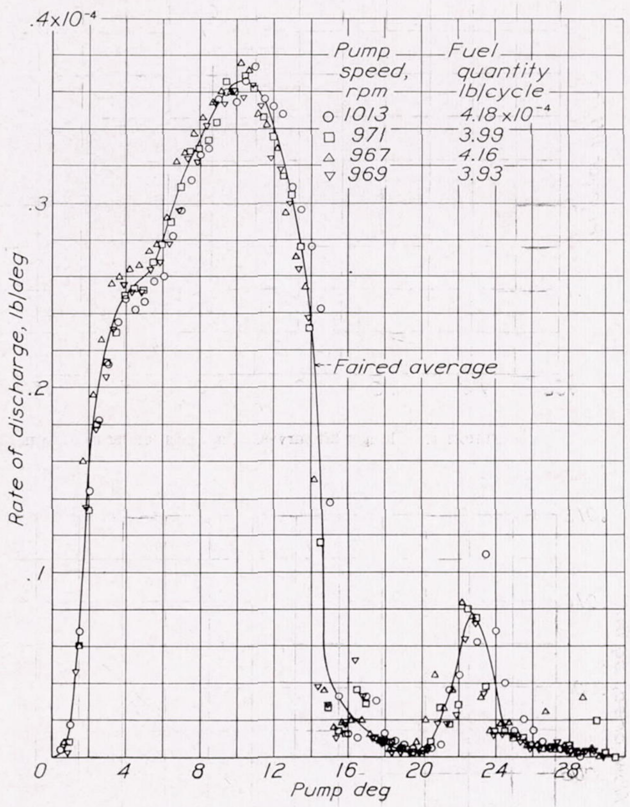


FIGURE 4.—Comparison of rate-of-discharge data for quadruplicate test runs. Pump and check valve, Bosch; cam 1; plunger diameter, 0.394 inch; injection-valve opening pressure, 3500 pounds per square inch; orifice area, 0.000895 square inch.

that it could not be run close enough to the receiver vanes to obtain the necessary minimum clearance.

INJECTION PUMPS

Three different Bosch pumps were used in these tests: a one-cylinder unit with a 0.394-inch diameter plunger; a two-cylinder unit with a 0.394-inch diameter plunger and both cams in phase; and a six-cylinder unit with a 0.354-inch diameter plunger and cams phased 60° apart. Unless otherwise specified, all data from multicylinder pumps are for only one cylinder.

Plunger-lift curves for the two different cams investigated are shown in figure 5. These curves were plotted from the manufacturer's specifications. Fuel-displacement curves based on the plunger-lift curves of figure 5 are shown in figure 6. Characteristics of the bypass-port flow area are shown in figure 7. The data for this figure were calculated from the dimensions of the pump plungers and the pump cylinders used. The same curve is applicable to all pump units tested. The rate of opening of the bypass port is dependent upon this curve and the plunger-lift curves.

PUMP CHECK VALVES

Figure 8 (a) shows the Bosch check valve. The valve is constructed with a fluted guide and a lapped shoulder. Delivery does not begin until fuel pressure from the pump forces the valve upward far enough for the lapped shoulder to clear the seat. At the end of the discharge the lapped shoulder returns to its lowest position and partly releases the pressure in the injection tube for the purpose of preventing dribble. No further discharge from the injection valve can take place except as the result of pressure-wave phenomena in the injection tube.

Figure 8 (b) shows an NACA design of a chec valve. Fuel flows through the ball check valve during delivery. Residual pressure in the injection tube can be adjusted to any desired value by changing the spring tension on the pressure-release valve. The valve was adjusted to open at 1000 pounds per square inch in these tests. The release of pressure waves from the injection tube into the inlet chamber of the injection pump set up pressure waves in the primary fuel system that adversely affected the charging of the pump cylinders and caused a variation of fuel quantity delivered per injection. Even charging of the pump cylinders was obtained by placing two surge chambers in the inlet and the outlet primary fuel lines to damp out the pressure waves. The chambers were placed close to opposite sides of the injection pump. Each chamber had an internal capacity of 140 cubic inches.

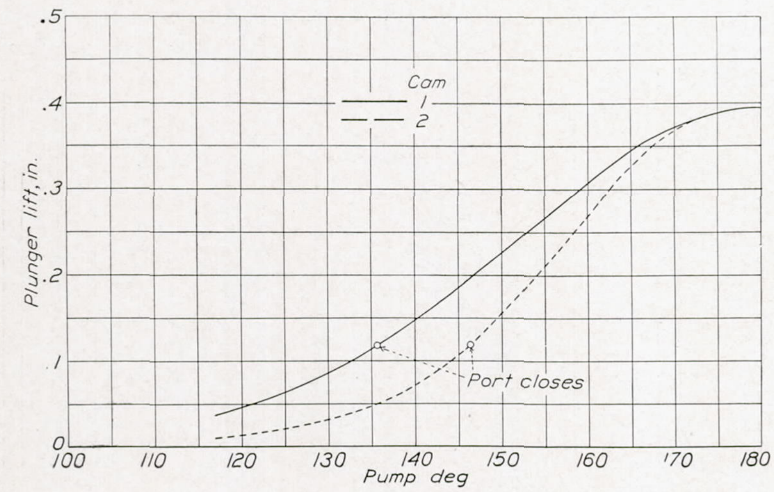


FIGURE 5.—Plunger lift curves. Cam position for maximum lift, 180°.

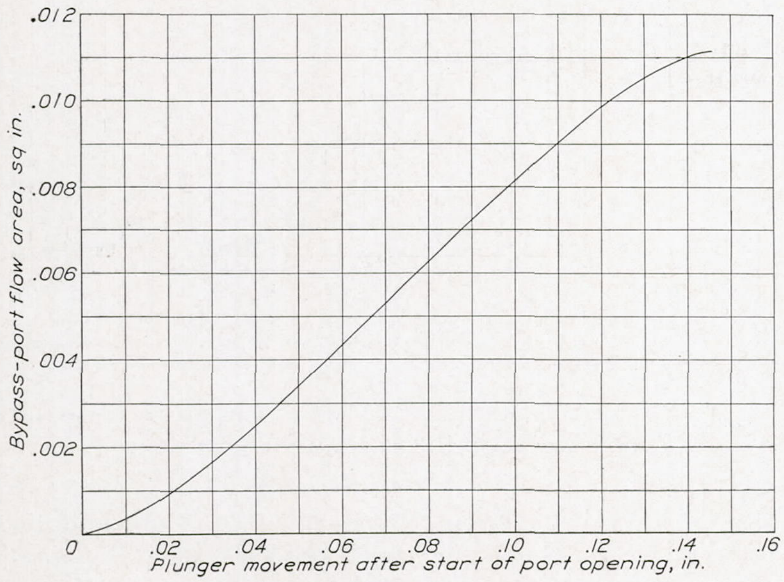


FIGURE 7.—Characteristics of the bypass-port flow area.

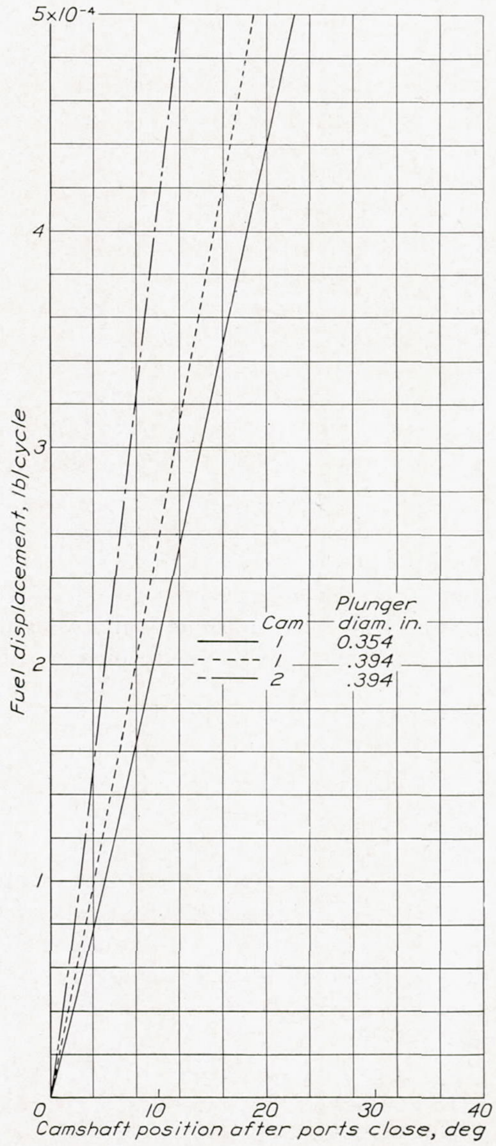
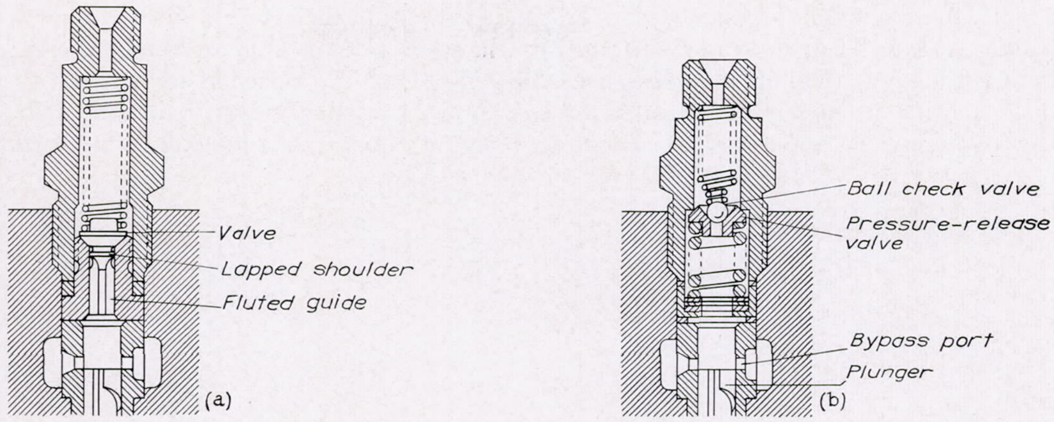


FIGURE 6.—Fuel-displacement curves for various combinations of cam outline and plunger diameter.



(a) Bosch design. (b) NACA design.

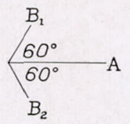
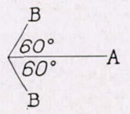
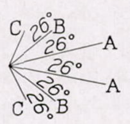
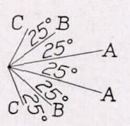
FIGURE 8.—Pump check valves.

Unless otherwise noted in the text, the following equipment and conditions were held constant throughout the rate-of-discharge tests:

1. Injection pump: plunger diameter, 0.394 inch
2. Injection tube: steel; inside diameter, 0.125 inch; outside diameter, 0.25 inch; single tube from pump outlet to injection valve
3. Injection valve: NACA injection valve 13; differential area type; sectional diagram shown in reference 4
4. Injection nozzles: multiple-orifice type; all orifices in same plane; characteristics appear in table I
5. Fuel: Diesel oil; 0.83 specific gravity at 68° F; 41 seconds Saybolt Universal viscosity at 80° F; 62 cetane number

TABLE I

NOZZLE CHARACTERISTICS

Orifice arrangement	Total orifice area (sq in.)	Orifice diameter (in.)
	0.000661	A = 0.023; B_1 = .012; B_2 = .013
	0.000605	A = 0.023; B = .011
	0.000868	A = 0.016; B = .010; C = .014
	0.000895	A = 0.020; B = .011; C = .007

Rate-of-discharge tests were run for all conditions listed in table II. All rate-of-discharge data and curves that show the weight of fuel discharged were plotted against pump degrees.

TABLE II

RATE-OF-DISCHARGE TESTS

Variable test condition	Speed of pump (rpm)	Fuel quantity (lb/cycle)	Plunger diameter (in.)	Injection-tube arrangement	Cam	Check valve	Orifice area (sq in.)	Valve opening pressure (lb/sq in.)	Figure
Fuel quantity	1250	2.80–4.54	0.394	Single	1	Bosch	0.000868	3500	9
Do	1250	2.80–4.32	.394	do	2	do	.000868	3500	10
Do	1250	2.92–4.35	.394	do	2	NACA	.000868	3500	11
Do	2400	1.91–4.04	.394	do	1	do	.000605	3000	12
Injection system	1800	4.07	.394; .354	Y; Single	1	do	.000661; .000605	3000	13

TEST ENGINE

The single-cylinder, water-cooled, two-stroke-cycle compression-ignition engine described in reference 5 was used in the engine performance tests. The 4⅝ by 7-inch cylinder admits air through circular inlet ports at the bottom of the cylinder and exhausts through four poppet valves in the cylinder head.

The following engine conditions were maintained constant during these tests:

1. Compression ratio based on swept volume, 13.7
2. Valve and port timing (deg A. T. C.): exhaust opens, 91; exhaust closes, 223; inlet opens, 129; inlet closes, 231
3. Inlet-port dimensions: height, 1 inch; diameter of ports, 11/32 inch; number of ports, 63; entry angle, 56° to radial; cylinder-liner thickness at port band, 3/16 inch
4. Maximum cylinder pressure: 1000 pounds per square inch. Engine-performance tests were made with the following injection systems: Bosch pump with one 0.354-inch-diameter cylinder connected to a single injection valve; Bosch two-cylinder pump having both cams in phase, with Y-tube connection to a single-injection valve

Comparable engine-performance tests were made with two different rates of fuel injection obtained by the use of the two different fuel-injection systems. The effect of fuel quantity on engine performance for both injection systems was determined with an engine speed of 1800 rpm and a scavenging-air pressure of 20 inches of mercury.

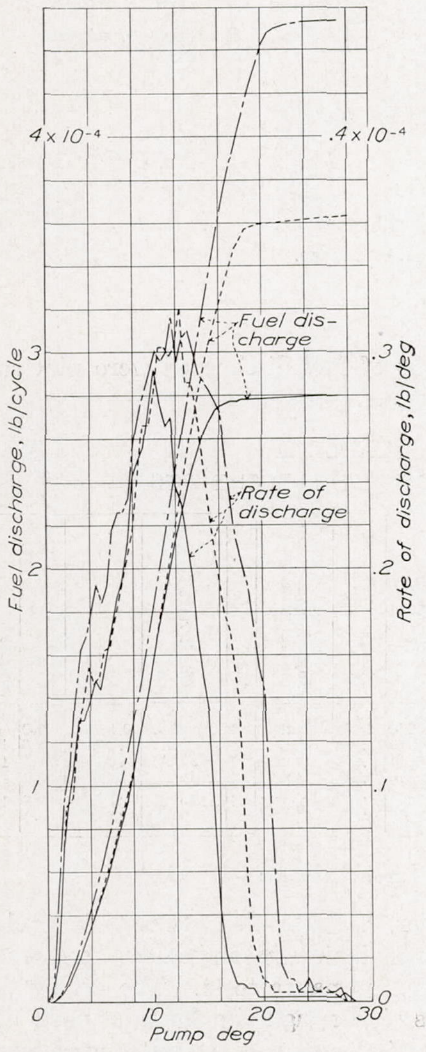


FIGURE 9.—Discharge characteristics with Bosch check valve and cam 1. Pump speed, 1250 rpm; injection-tube length, 31 inches; injection-valve opening pressure, 3500 pounds per square inch; orifice area, 0.000868 square inch.

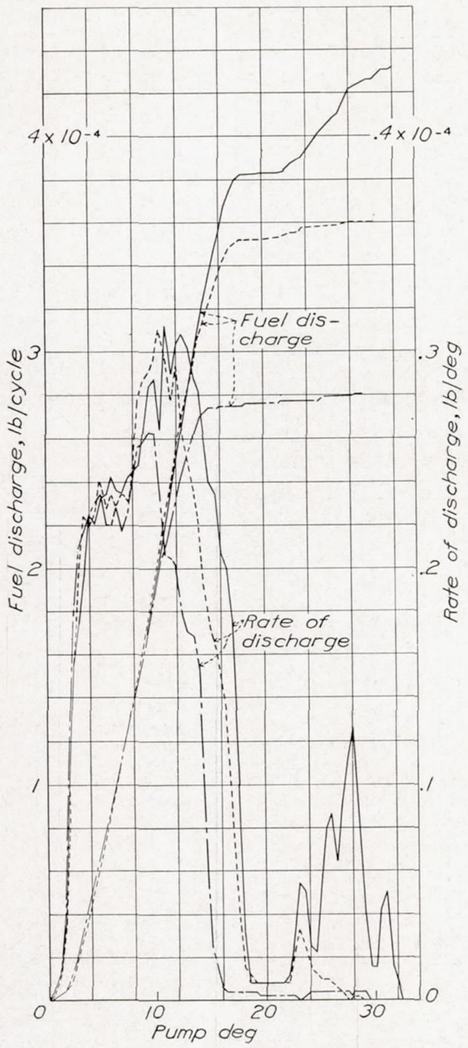


FIGURE 10.—Discharge characteristics with Bosch check valve and cam 2. Pump speed, 1250 rpm; injection-tube length, 31 inches; injection-valve opening pressure, 3500 pounds per square inch; orifice area, 0.000868 square inch.

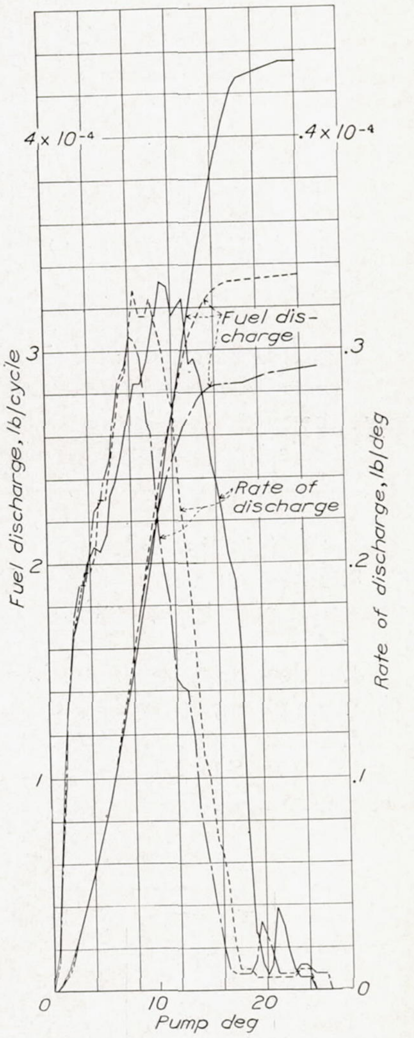


FIGURE 11.—Discharge characteristics with NACA check valve and cam 2. Pump speed, 1250 rpm; injection-tube length, 31 inches; injection-valve opening pressure, 3500 pounds per square inch; orifice area, 0.000868 square inch.

RESULTS AND DISCUSSION

RATE OF DISCHARGE

Effect of pump check valve.—A considerable number of injection-valve stem-lift diagrams of injection systems equipped with the Bosch check valve, with a plain ball check valve, and with no check valve are shown in reference 3. In the present tests a critical rate of plunger motion was found above which secondary discharges occurred. (See figs. 9 and 10.) The secondary discharges resulted from fuel pressure waves in the injection tube caused by the elasticity and the inertia of the fuel. More complete information on this phenomenon is given in reference 6. A brief description of the action is as follows: Pressure waves, which are originally set up by the plunger, travel through the fuel in the injection tube at the rate of approximately 50,000 inches per second. When the pressure wave reaches the injection nozzle, any energy of the wave that is not dissipated in discharge of fuel through the orifice is reflected toward the pump. The back-rushing wave after reaching the pump plunger is reflected and again traverses the tube toward the injection valve. A conventional type of pump check valve such as the Bosch check valve, which prevents return of fuel from the injection tube to the pump cylinder after cut-off, will completely reflect residual pressure waves in the injection tube. If these waves are of sufficient intensity, they will open the injection valve repeatedly and cause secondary discharges to occur. These pressure waves are dissipated by the release of fuel in the secondary discharges, and the discharges cease when the pressure waves are no longer great enough to open the injection valve.

The NACA check valve was designed to reduce secondary injections and yet maintain a residual pressure in the injection tube. Pressure waves reflected from the injection valve are partly dissipated at the pump end of the injection tube by the release of fuel through the pressure-release valve, the plunger barrel, and the bypass port into the primary fuel chamber. It was found that a maximum residual pressure equal to one-third of the injection-valve opening pressure could be maintained with this check valve without excessive secondary discharges. The data of figure 11 were taken with an injection system using the NACA check valve and are comparable with the data of figure 10 for the Bosch check valve. The NACA check valve was used with pump speeds up to 2400 rpm without large secondary discharges. (See fig. 12.) Inasmuch as difficulty was experienced in obtaining an even charging of the pump cylinders when using this check valve, a word of caution in regard to its use is advisable. Sufficient pump inlet-chamber capacity is necessary to damp out pressure waves or they will cause large variations in fuel quantity with change of pump speed or slight unevenness of fuel quantity at constant pump speed.

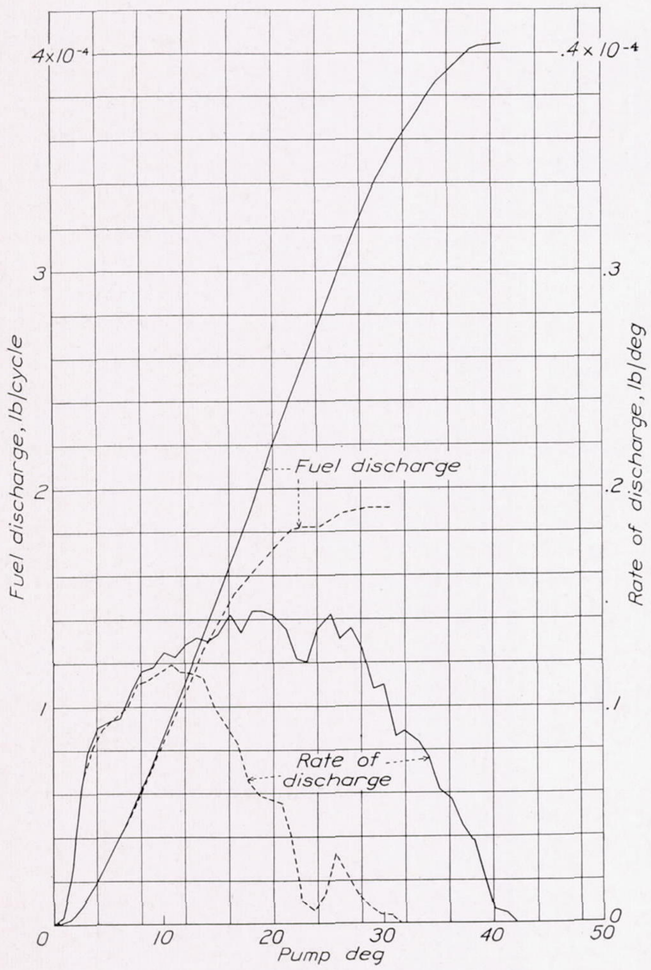


FIGURE 12.—Effect of fuel quantity on discharge characteristics at a pump speed of 2400 rpm. Check valve, NACA; cam 1; injection-tube length, 44 inches; injection-valve opening pressure, 3000 pounds per square inch; orifice area, 0.000605 square inch.

ENGINE PERFORMANCE

Figure 14 shows a comparison of the performance of the two-stroke-cycle compression-ignition engine for the two injection systems for which rate-of-discharge data are shown in figure 13. The injection nozzles were of comparable design except for the total discharge-orifice area. (See table I for characteristics.) The larger orifice area was used with the two-cylinder injection pump to allow injection of a full-load fuel quantity without exceeding the safe delivery pressure of the injection pump. The higher rate of injection gave an increase of 7.6 percent in maximum gross brake mean effective pressure and a reduction of 6.2 percent in the minimum gross brake specific fuel consumption from that obtained with the lower injection rate. The injection advance angle was 2° to 4° less with the

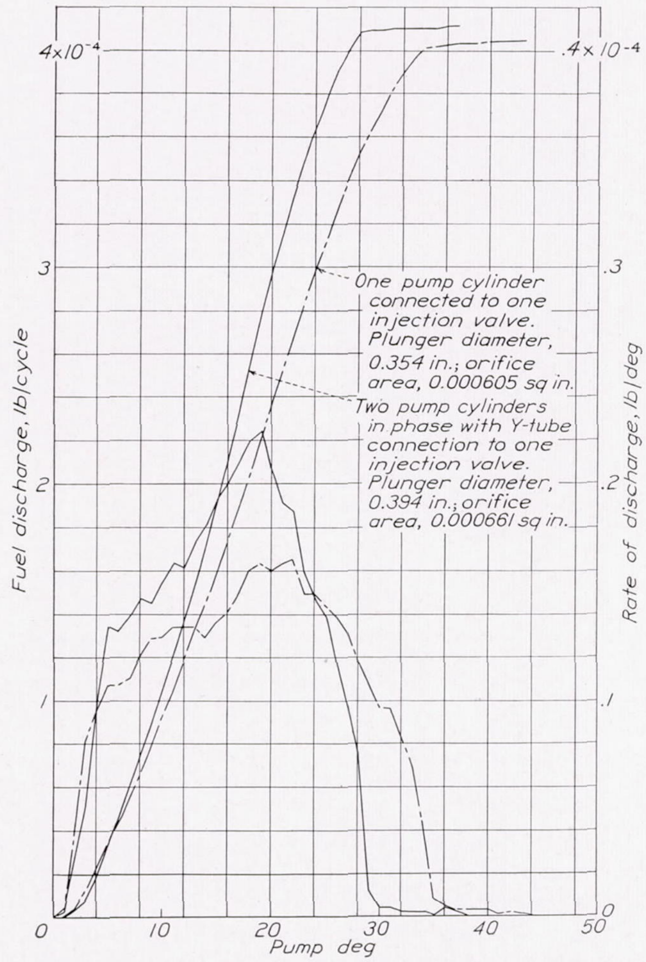


FIGURE 13.—Comparison of injection characteristics for two arrangements of the injection system at a pump speed of 1800 rpm. Check valve, NACA; cam 1; injection-valve opening pressure, 3000 pounds per square inch. Injection-tube lengths: plunger to Y, 6.5 inches; plunger to orifice, 44 inches.

higher rate of injection, which indicates that the rate of pressure rise in the combustion chamber was greater. The lesser fuel consumption with the higher rate of injection was due to the burning of a greater percentage of fuel in the early part of the stroke where the expansion ratio is high. These data indicate that an improvement in engine performance can be expected by

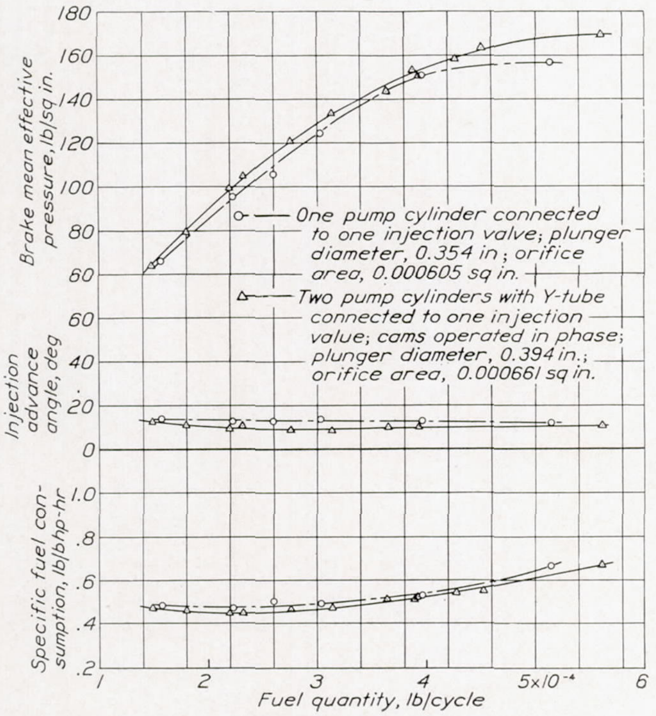


FIGURE 14.—Comparative effect of rate of fuel injection on the performance of a two-stroke-cycle compression-ignition engine obtained with two different injection systems. Engine speed, 1800 rpm; check valve, NACA; injection-valve opening pressure, 3000 pounds per square inch. Injection-tube lengths: plunger to Y, 6.5 inches; plunger to orifice, 44 inches.

increasing the maximum rate of injection and shortening the injection period.

Changing from the lower to the higher rate of fuel displacement in this case caused a change in the shape of the rate-of-discharge curve that tended to make it conform more nearly with the desired rate-of-injection curve. It is believed that the rate-of-injection curve should increase as a function of the rate of volume change in the engine cylinder to a maximum value and then return instantaneously to zero. Further tests will be made to determine the correctness of this assumption.

CONCLUSIONS

1. The rate-of-discharge apparatus used in these tests consistently reproduced its own average data for repeated test conditions within ± 4 percent. Satisfactory operation was obtained with pump speeds up to 2400 rpm; satisfactory operation with higher speed was indicated.

2. Secondary discharges were practically eliminated at all operating conditions by use of a combination check valve and pressure-release device.

3. Engine performance improved with increased rate of injection and decreased injection period.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *March 24, 1941.*

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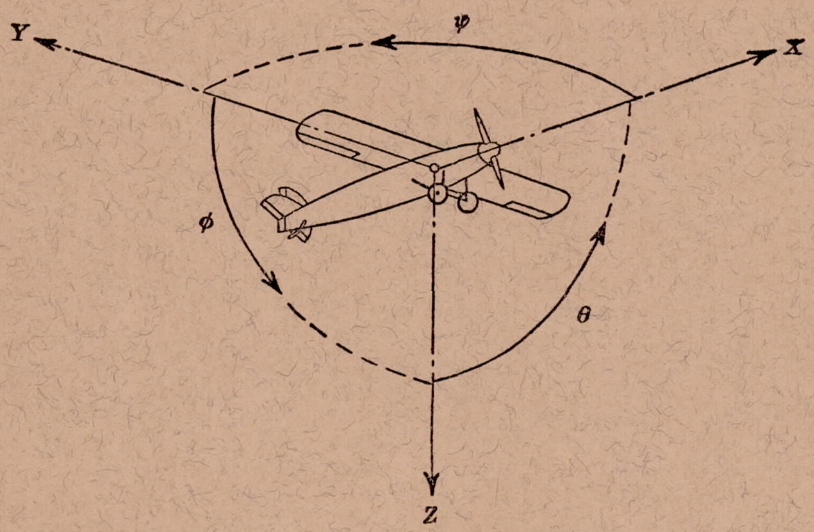

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h.

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.