THE STUDY OF DESIGN FACTORS FOR AUTOMATICALLY CONTROLLING SPARK-IGNITION ENGINES

by 500

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ABBREVIATIONS

btc	before top centre
bhp	brake horsepower
bmep	brake mean effective pressure
bsfc	brake specific fuel consumption
psia	pounds per square inch, absolute
rpm	revolutions per minute
r	compression ratio
Fig.	figure
°R	degree Rankine
hr	hour
%	per cent
hp	horsepower
lbm	pound mass
F_R	relative fuel-air ratio
η	efficiency
deg	degree

CHAPTER I

INTRODUCTION

Spark-ignition engines are widely used in automobiles, in aircraft, and as marine engines. As the use of the spark-ignition engines has increased, it has become necessary to make changes in the design of the engine, and in the design of the control systems, so as to get the best possible performance for the entire operation range of the engine.

New developments in the fuel control of the spark-ignition engine include new designs of carburetors and fuel-injection methods. The performance of the engine with a carburetor has been satisfactory except for the problems of air-pollution and efficiency. The main difficulty is to maintain a fuel-air ratio for all load and speed conditions that will give best efficiency and complete combustion.

The fuel-injection system offers a more direct control of fuel-air ratio than the carburetor. If the optimum fuel-air ratio can be maintained for each load condition, the engine will operate at high efficiency and less pollutants in the exhaust gases. Since an automobile engine is required to operate at different speeds, different loads, and different ambient conditions, the problem of control becomes very complex.

The engineers of Volkswagen have designed and have in production a fuel-injection system, automatically controlled through an electronic computer (1). The computer maintains a fully controlled and properly metered flow of fuel and air to the cylinders for best performance at all load conditions, and reduces the emission of unburned hydrocarbons and carbon monoxide to such a low level that other antismog devices are not required. It is the purpose of this report to develop the specifications for an electronically controlled fuel-injection system and to explain the design factors of the electronic control unit.

CHAPTER II

EFFECT OF OPERATING VARIABLES ON PERFORMANCE OF SPARK-IGNITION ENGINE

(1) Effect of fuel-air ratio on performance

Although various ratios of fuel and air can be burned in the engine, it is found that a definite ratio of fuel and air is required to obtain maximum mean effective pressure at a given speed. Fig. 1 and Fig. 2 show the effect of fuel-air ratio on brake mean effective pressure, and on brake specific fuel consumption. As the fuel-air ratio is increased (with best spark-timing), brake mean effective pressure is increased. Brake mean effective pressure goes on increasing as the fuel-air ratio is increased, until a point which is near to chemically correct fuel-air ratio point. Beyond this point if fuel-air ratio is increased, brake-mean effective pressure is decreased because combustion of fuel is not complete due to insufficient amount of air and hence optimum release of chemical energy is not obtained (2).

(2) Effect of engine speed on performance

As the speed of the engine is increased, brake horsepower is also increased. Torque is not strongly dependent on the speed of the engine, but mainly dependent on the size of the engine, but as the brake horse is proportional to the product of torque and speed, horsepower is increased as the speed.

Fig. 3 shows the effect of engine speed on brake horsepower, brake specific fuel consumption, brake mean effective pressure, and brake torque (8).

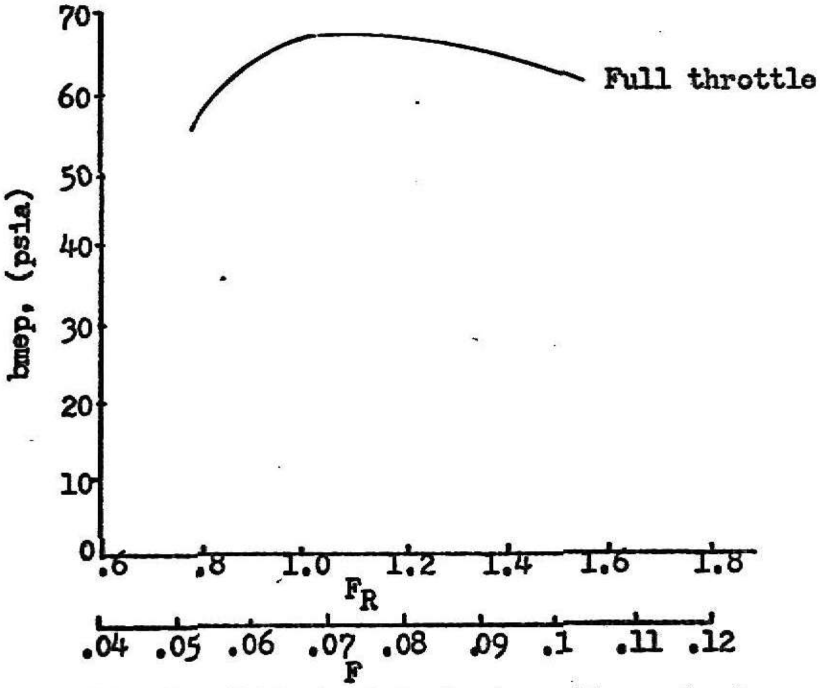

Fig. 1. Effect of fuel-air ratio on brake mean effective pressure

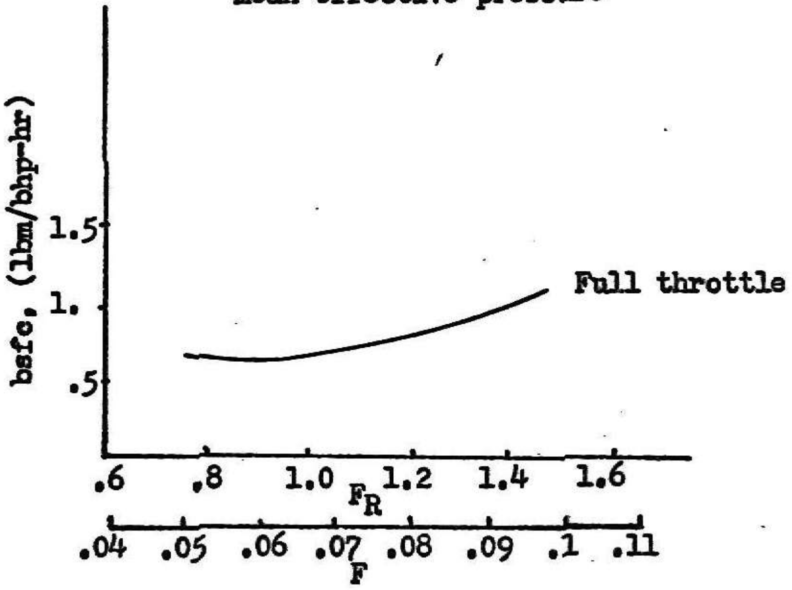

Fig. 2. Effect of fuel-air ratio on brake specific fuel consumption

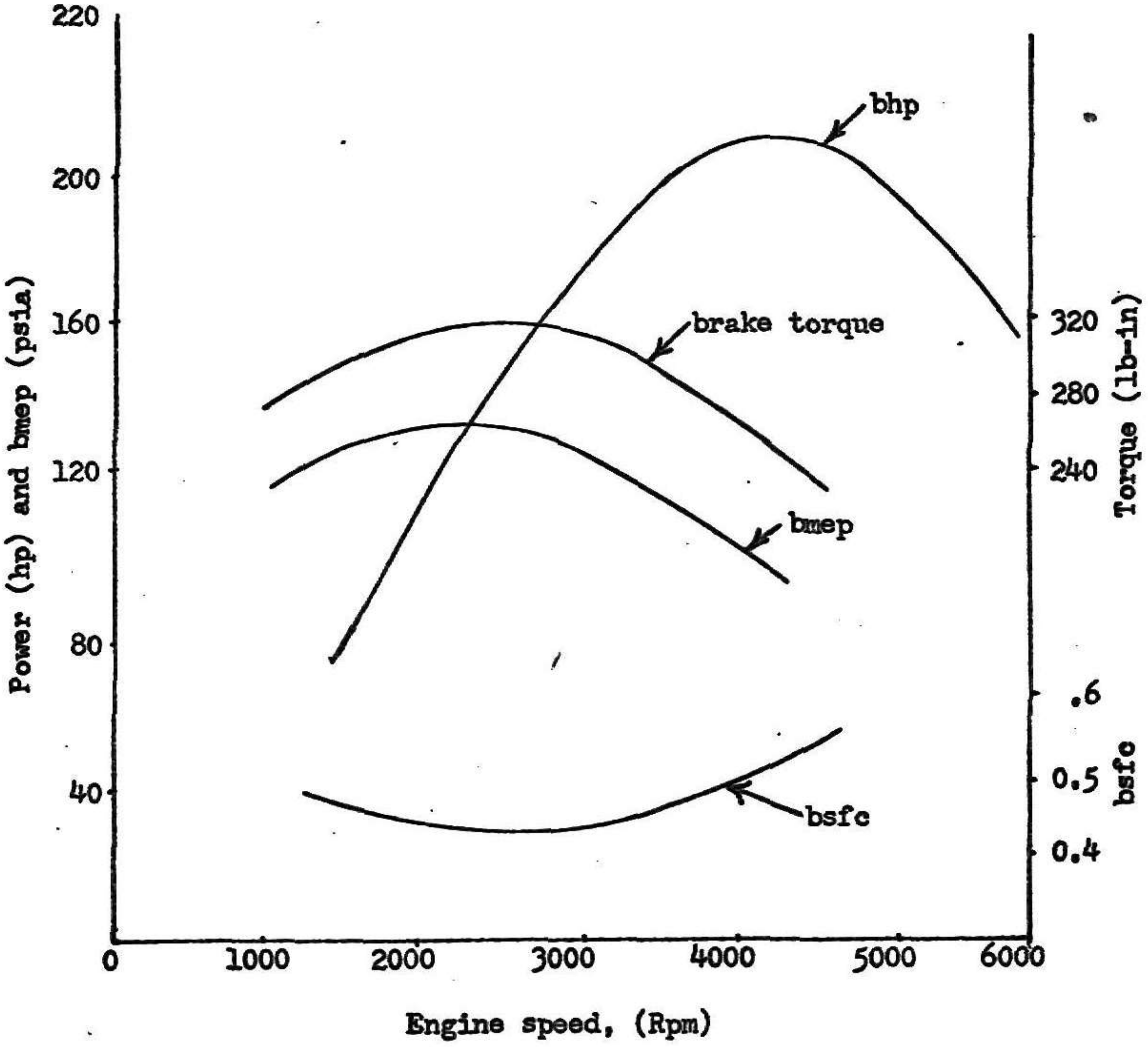

Fig. 3. Effect of speed on bmep, bhp, brake torque, and brake specific fuel consumption

Similar results were obtained by an experiment performed on a C.F.R. engine (installed in Mechanical Engineering Laboratory) with a fuel-injection system. Torque and mean-effective pressure curves peak at a speed, about half that of the peak horsepower. Minimum brake specific fuel consumption was obtained near the midrange of speed.

(3) Effect of compression ratio on performance

Compression ratio is the major factor contributing towards detonation in spark-ignition engines. As the compression ratio is increased, the peak pressure of the cycle is increased and hence the peak temperature is increased, which reduces the end-gas reaction time, so a tendency towards detonation is increased. This fact is graphically shown in Fig. 4.

The curve of compression ratio vs. mean effective pressure shows that as the compression ratio is increased from 7.3, using nondetonating fuel, brake mean effective pressure is increased, as shown in Fig. 5 (2).

(4) Effect of spark-timing on performance

There is an optimum spark advance for all spark-ignition engines, which gives maximum power output for given operating conditions. Any factor of engine design or operation that increases the crank degrees required for combustion will also require an increase in spark advance.

As the speed of the engine increases, the speed of flame propogation in combustion chamber also increases, which in turn increases the number of crank degrees required for combustion and hence the spark should be advanced more.

Fig. 6 shows the effect of spark-timing on brake mean effective pressure with no detonation. Departure on either side, from maximum power spark-timing at a given speed reduces power output (2).

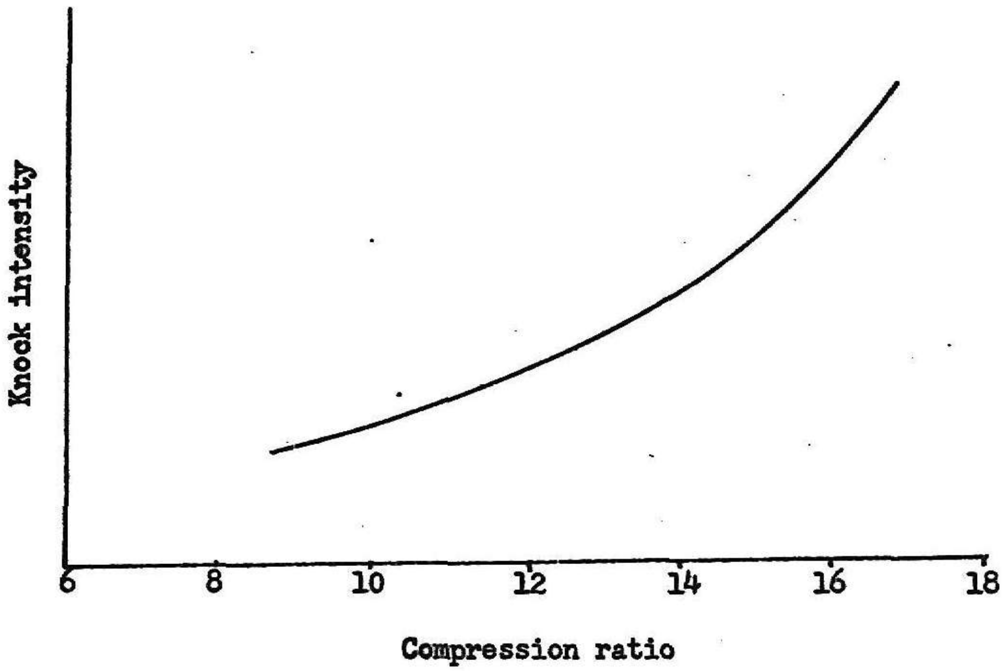

Fig. 4. Effect of compression ratio on knock intensity

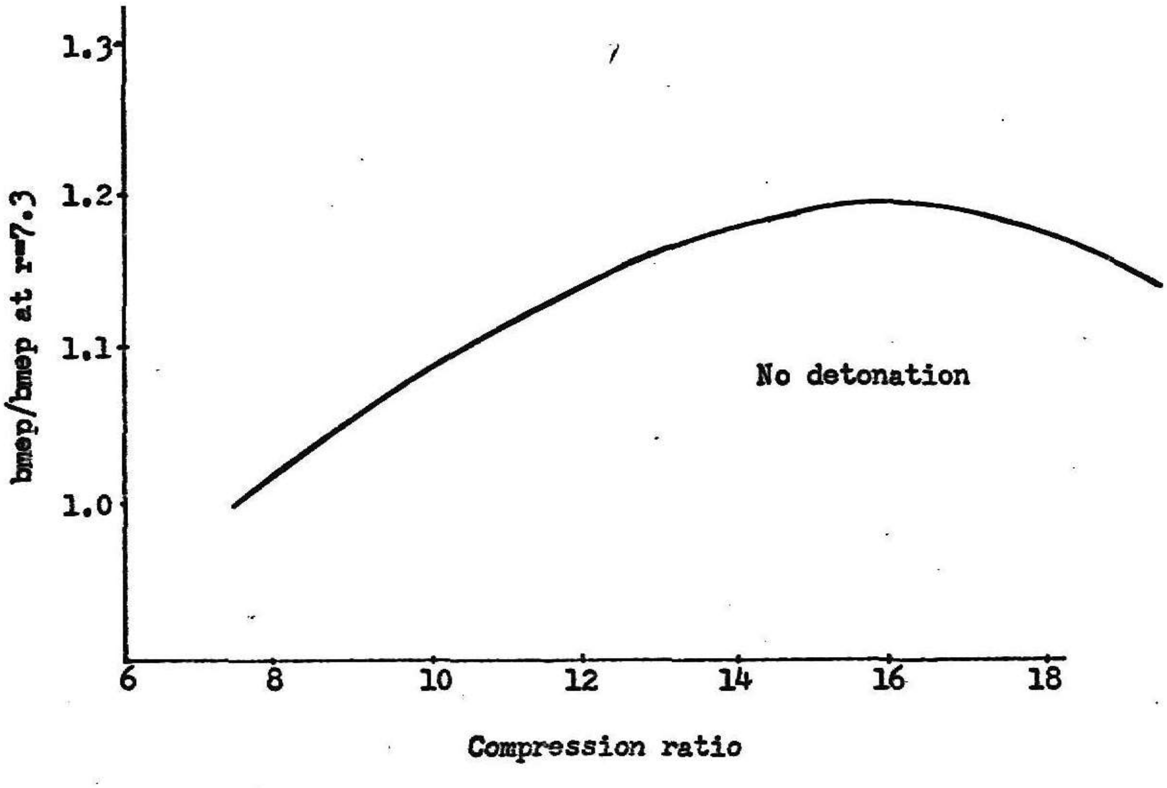

Fig. 5. Effect of compression ratio on bmep

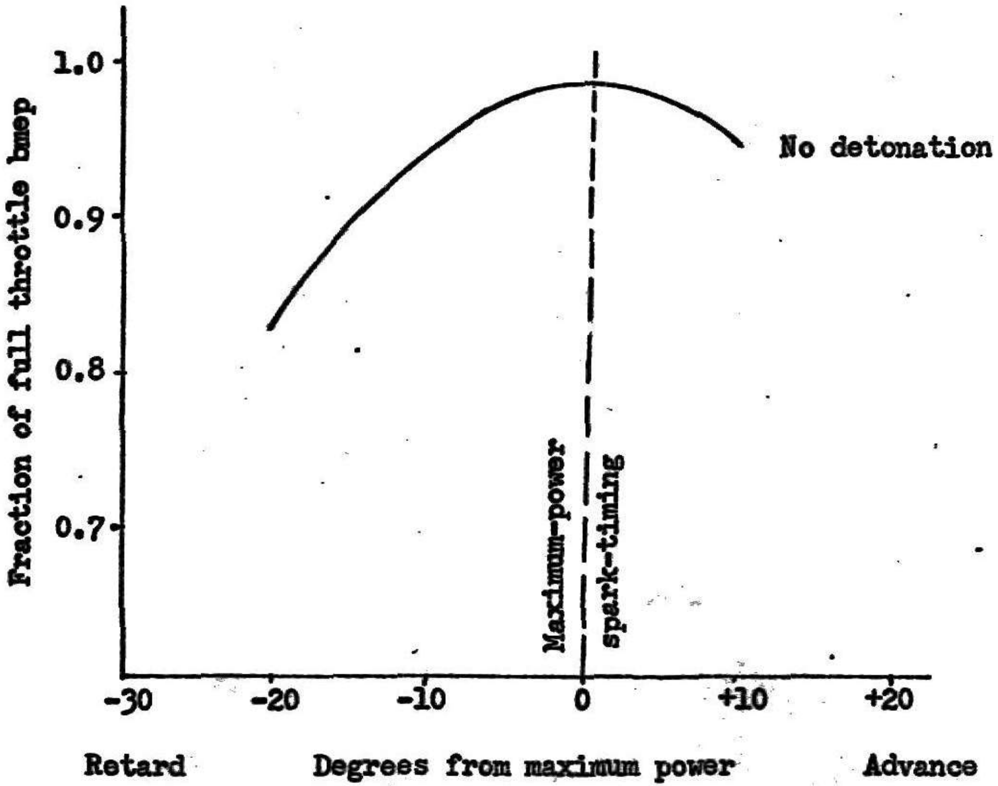

Fig. 6. Effect of spark-timing on bmep in a passenger-car engine with no detonation

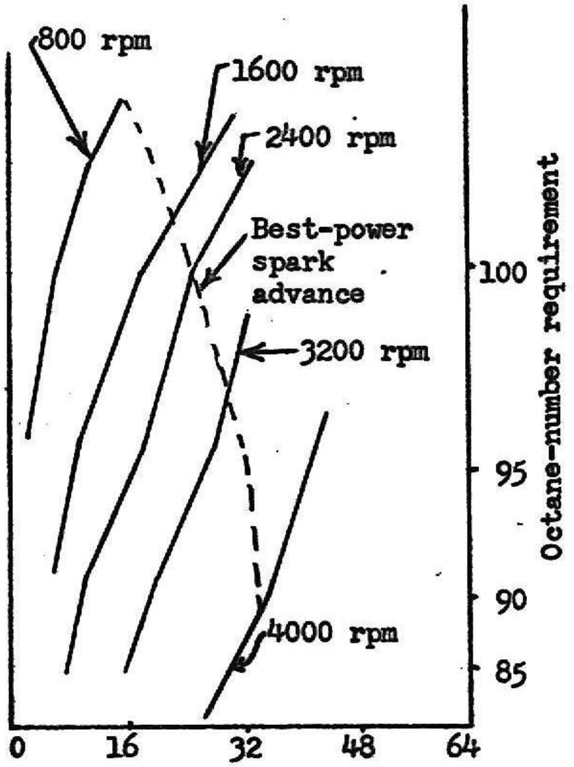

Fig. 7. Ignition timing, deg. btc

A retarded spark is a powerful means of controlling detonation. At a given speed, the octane requirement increases rapidly as spark-timing is advanced, because the peak pressure and hence temperature at peak pressure increases, which tends to increase detonation. Fig. 7 shows the effect of spark advance on octane number requirement at different speeds (2).

(5) Effect of atmospheric temperature on performance

Fig. 8 shows the effect of changes in atmospheric temperature on engine output. At fixed throttle and in absence of detonation limit, brake mean effective pressure is nearly proportional to square root of inlet temperature (2).

(6) Effect of humidity on performance

Humidity affects the following factors:

(1) Inlet air density
(2) Combustion fuel-air ratio
(3) Indicated thermal efficiency
(4) Volumetric efficiency
(5) Detonation limits

Fig. 9 shows the curves of indicated thermal efficiency vs. humidity for a carbureted spark-ignition engine with constant inlet temperature and inlet pressure, constant spark timing, constant carburetor adjustment and no detonation. Indicated thermal efficiency decreases as the humidity increases.

(7) Effect of altitude on performance

The effect of altitude on engine performance is of great importance for aircraft engines and for engines to be operated in mountainous regions.

At high altitudes, atmospheric temperature and pressure decreases and hence the density of inlet air decreases. Fig. 10 shows the effect of inlet air density on brake mean effective pressure of an aircraft engine. Indicated

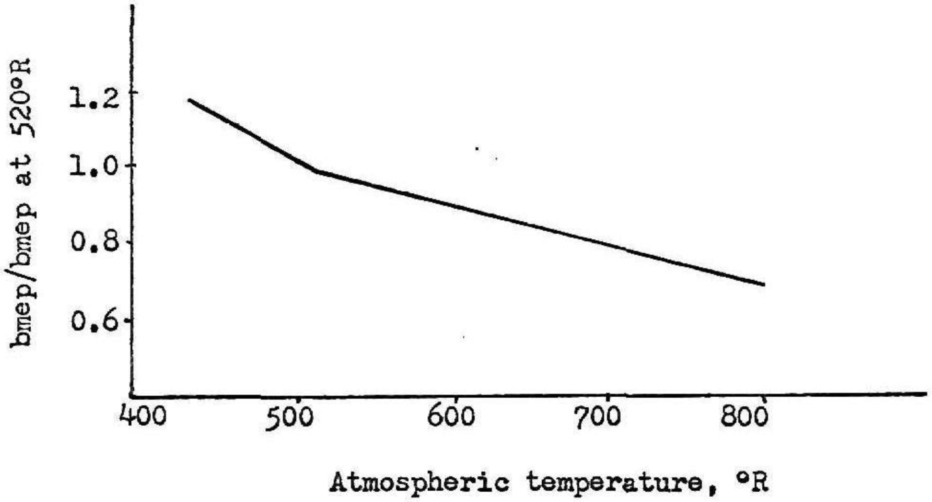

Fig. 8. Effect of atmospheric temperature on engine output

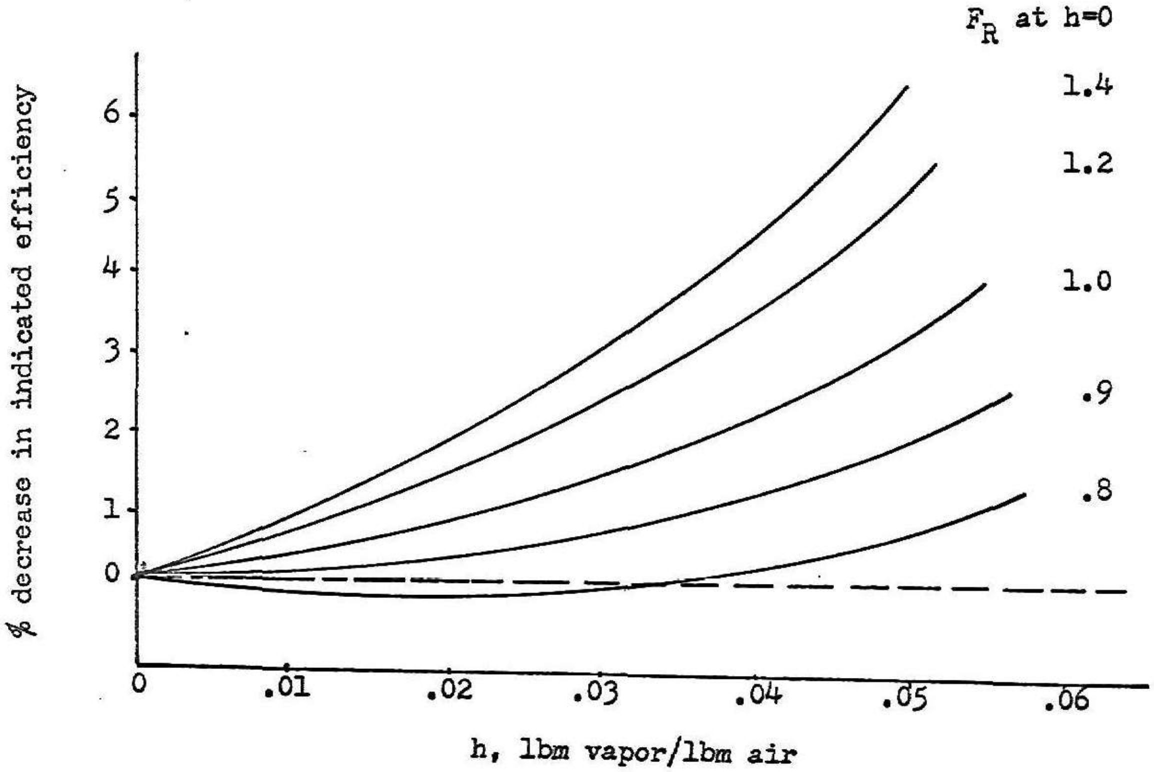

Fig. 9. Effect of humidity on indicated efficiency

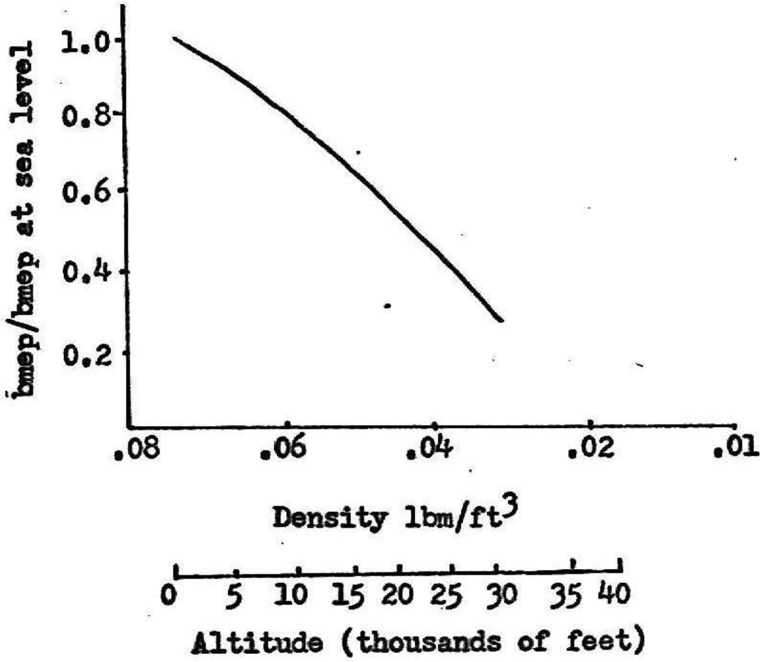

Fig. 10. Effect of altitude on bmep

specific fuel-consumption remains constant over a wide range of inlet air density, provided distribution of mixture in different cylinders of multi-cylinder engine is not affected. For this reason, it would be better to use fuel-injection to individual cylinders (2).

CHAPTER III

PERFORMANCE OF SPARK-IGNITION ENGINE WITH CARBURETOR AND FUEL-INJECTION

The mixture requirements of a spark-ignition engine, for various phases of operation, depend on the speed of the engine, load on the engine, ambient conditions, and whether the engine is used for steady running conditions or transient operations. Steady running conditions mean continuous operation at a given speed and power output with normal engine temperatures. Transient operations include starting, warmup, and the process of changing from one speed or load to another, as in an automobile engine.

A carburetor is one of the devices used for introducing fuel-air mixture into the combustion chamber of spark-ignition engine. The basic purpose of a gasoline carburetor is to deliver to the intake manifold a mixture of fuel and air in the proper quantity and quality, both chemically and physically, which could be easily and readily controlled, distributed, and consumed by the engine.

To accomplish the above purposes, the carburetor must function in the following ways (7):

(1) It must accurately measure the amount of air drawn in by the engine and meter the fuel into the air stream in proportion to this quantity of air.

(2) It must assist distribution by discharging the liquid fuel into the air-stream in the form of an atomized spray.

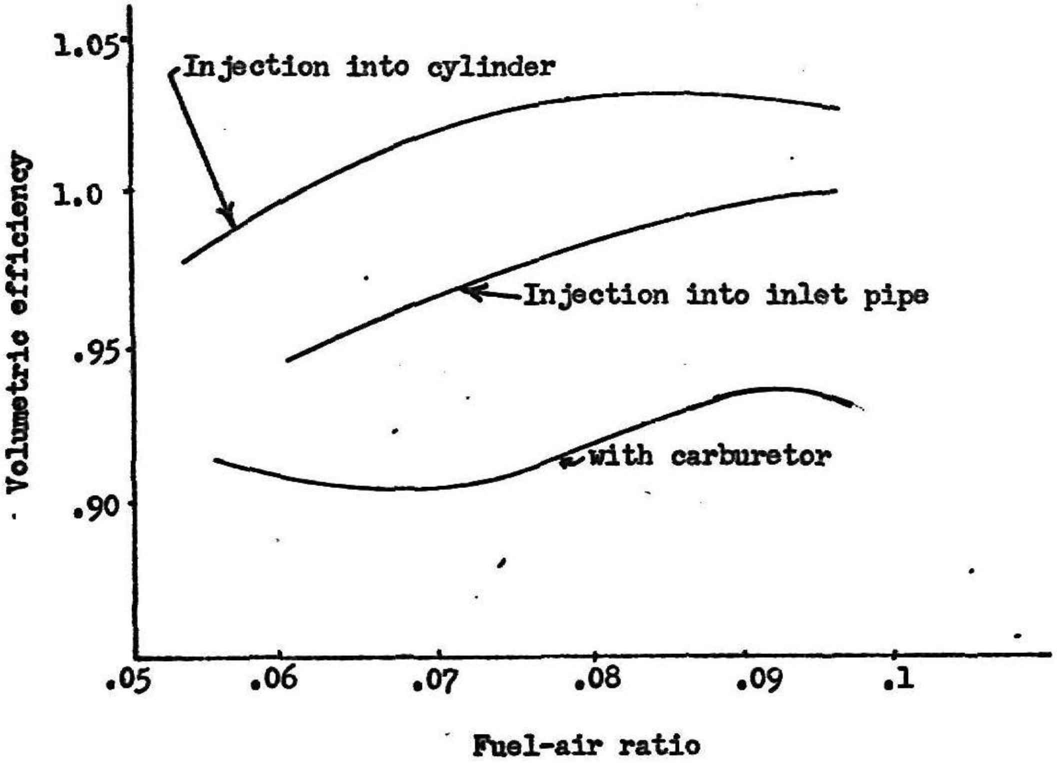

Fig. 11. Effect of fuel-injection on volumetric efficiency

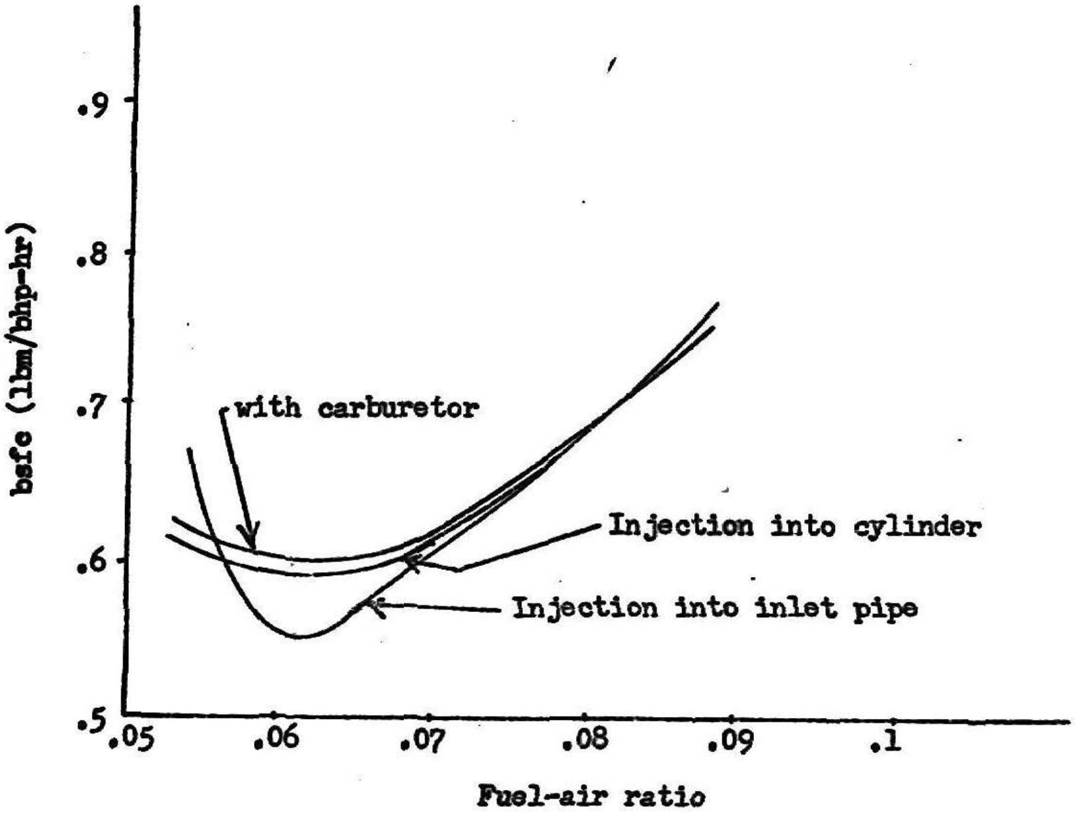

Fig. 12. Effect of fuel injection on specific fuel-consumption

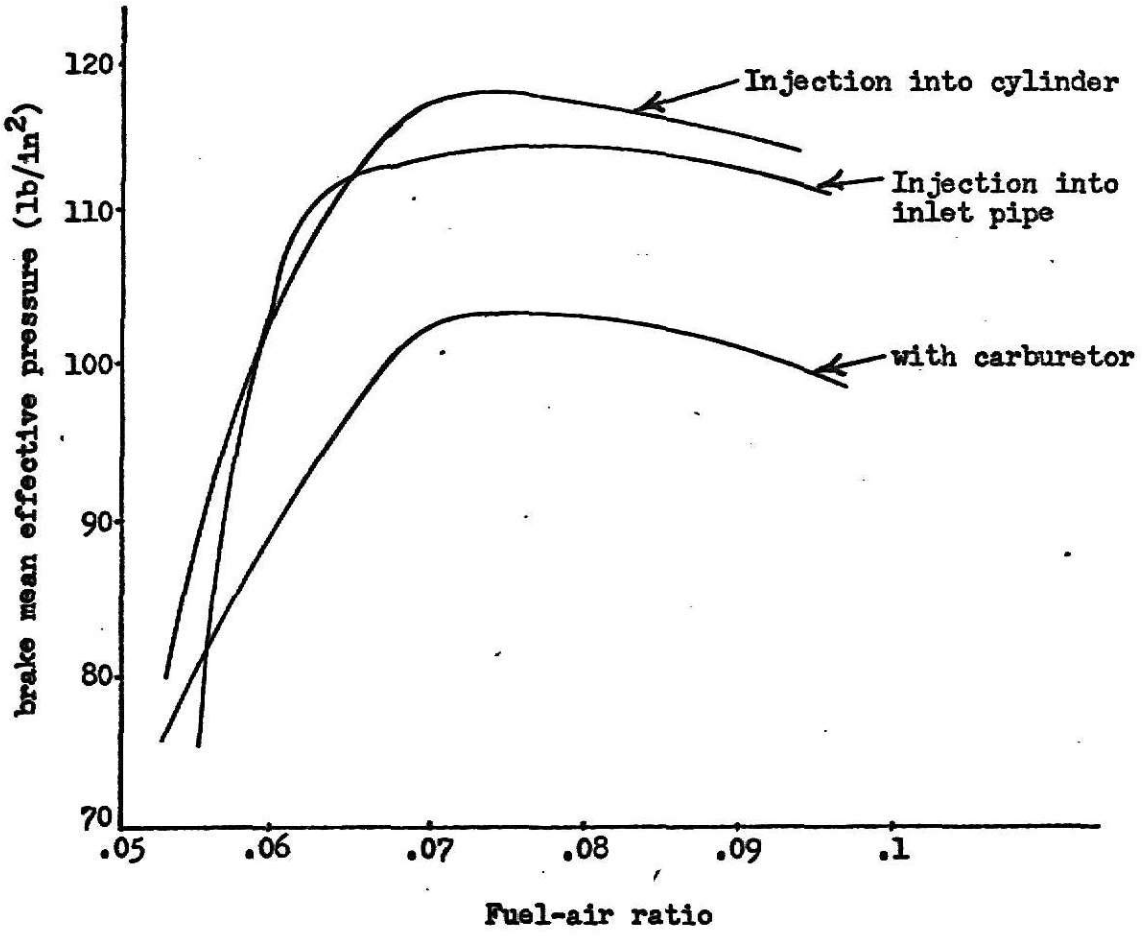

Fig. 13. Effect of fuel-injection on bmep

(3) It must provide a means for controlling power output and speed to meet the demands at various phases of operation of the engine, by varying the quantity of this mixture of fuel and air that is permitted.

Fuel-injection is the other device of introducing fuel into the combustion chamber of spark-ignition engines.

Experiments have shown that fuel injection either into the inlet pipe or into the cylinder is superior in performance to the usual type of carburetion (8).

Figs. 11, 12 and 13 show the performance curves of a spark-ignition engine (1) using a carburetor, (2) using injection into the inlet pipe, and (3) injection into the cylinder.

The outstanding indications of these performance curves are increase in maximum available power, increase in volumetric efficiency and fairly low specific fuel consumption when injection methods are used. The increase in power was partly due to the elimination of the pressure drop through the carburetor and partly due to direct effect of the spray itself. The increase in volumetric efficiency was due to higher pressure drop in the cylinder which causes a large flow of air into the cylinder and hence the volumetric efficiency was increased.

Advantages of fuel-injection over carburetion

Though the function in both cases is similar, fuel-injection has proved very efficient. Following are the notable advantages of fuel-injection over the carburetion (5):

(1) Fuel Distribution:-In carburetor equipped engine, the manifold has

to carry fuel-air mixture to a variety of sizes and lengths of passages and hence it is very difficult to feed each cylinder in equal amounts. There will be a considerable difference in the fuel-air ratio between the leanest cylinder and the richest cylinder of a given engine. In fuel injection, fuel can be fed under pressure through a set of calibrated nozzles, one for each cylinder, so that the fuel charge for each cylinder is equal.

(2) Air Flow:-At idle, air flow is small and in order to keep the gasoline mixed with the air, it is necessary to have small passages to keep up the air velocity. On the other hand, when power is required, a larger manifold passage is desirable to allow maximum breathing of the engine. In order to meet both these requirements, the manifold should be of medium size, which has limited both low and high speed performance.

In the case of fuel injection, the manifold would not have to carry a fuel/air mixture and therefore could be designed of desired size.

(3) Horsepower:-Carburetion systems have practical limits in size of venturi, number of cores, etc. and so it has become difficult to maintain efficiency in the part throttle operation.

Since a fuel-injection system could supply almost unlimited quantities of fuel and air, more efficient engine performance could be obtained.

(4) Air Pollution:-During starting and warmup period, a very rich mixture is required. In the carburetion system, the fuel supply is not cut off completely during deceleration and hence the amount of

hydrocarbons and carbon monoxide exhausted is considerable. With fuel-injection, the control over air pollution, due to automotive emission, can be achieved by completely cutting off the fuel supply, during deceleration.

CHAPTER IV

TYPES OF FUEL-INJECTION SYSTEMS

Two basic methods of injecting fuel are: (1) common-rail injection system and (2) pump injection system.

Common-rail injection system

The line-diagram of common-rail injection system is shown in Fig. 14 (6). In this system, a constant pressure is maintained in the "common-rail" or manifold, that supplies fuel to all cylinders of a multicylinder engine. A single pump is used for all cylinders, to maintain a constant pressure. Fuel is injected into the cylinders when nozzle valves on individual cylinders are opened mechanically. The pump used in this system is of constant stroke, cam driven or electrically driven, and gives constant pressure and constant supply of fuel each time, so for a fixed size nozzle, the amount of fuel injected is dependent mainly on the length of time for which nozzle valve is kept open.

Considering constant pressure on the upstream side of the nozzle and assuming the pressure difference across the nozzle to be in critical range, and therefore independent of the downstream pressure, Bernoulli's equation gives mass of the fuel delivered in one injection (2):

$$M_f = CAt\sqrt{2\rho p g_o} = CA\sqrt{2\rho p g_o}\,\frac{\theta}{360N}$$

where:

M_f = mass of fuel delivered in one injection

C = average flow co-efficient of the nozzle

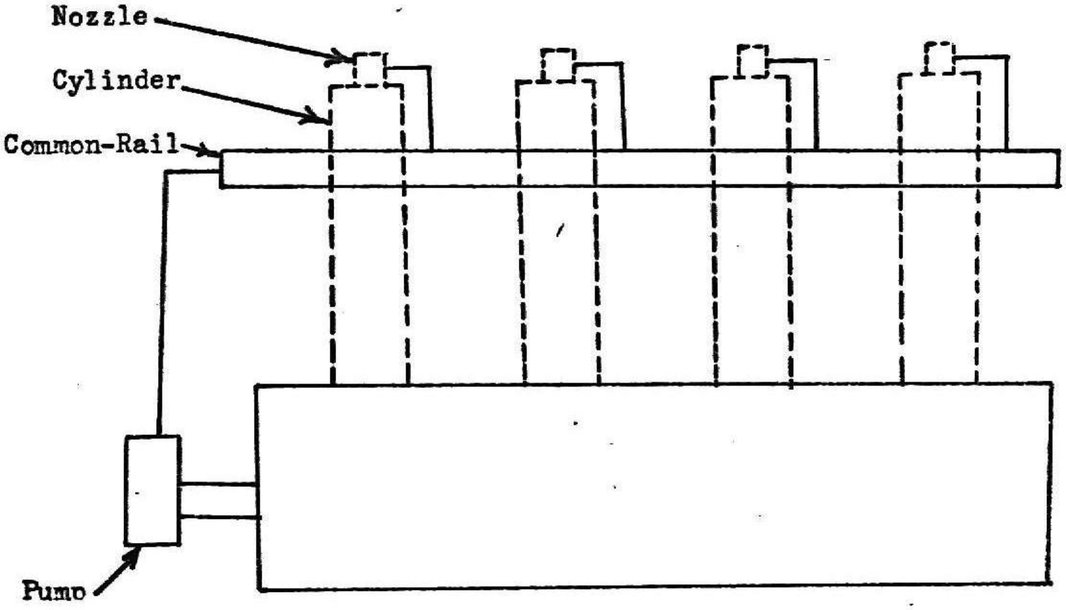

Fig. 14. Line diagram of Common-Rail fuel-injection system.

A = area of the nozzle cross section

p = upstream pressure

ρ = fluid density

g_o = force-mass acceleration constant

t = duration time, sec.

θ = duration angle, degrees

N = engine revolutions per minute

From the equation it is evident that the fuel quantity delivered in one injection is dependent on duration for which the nozzle valve is kept open.

<u>Pump injection system</u>

In a pump injection system, generally one pump per cylinder is preferred. The pump controls the exact quantity of fuel and the timing. Generally pumps are cam driven so one method of controlling the rate of feed of fuel is to change the shape of the cam.

A pump consists of an accurately ground steel barrel and a plunger which is piston fit in the barrel. Fuel is supplied through the inlet connection to the common supply in the pump casing, from there it is drawn into the pump barrel through the inlet port.

With the plunger at the bottom of the stroke, the fuel flows through the ports and completely fills the portion of the barrel above the plunger. The plunger moving upwards, closes the barrel ports. As the plunger continues its upward movement, the fuel under pressure opens the delivery-valve and flows into the injection tubing. When the pressure created by the fuel pump is above the nozzle-opening pressure, nozzle valve is opened and fuel is injected. As soon as the fuel-pressure drops below nozzle-opening pressure, the nozzle valve comes back on its seat and injection ceases.

The amount of fuel delivered by the pump in one injection can be changed by rotating the pump plunger so that the plunger's lower helix uncovers the bypass port earlier or later, as desired.

Electronic fuel injection system

To overcome the limitations associated with the carburetor engine and to have a more direct control over the operation of the engine a common fuel injection system, with electronically controlled fuel injection was developed. This system was first introduced by the engineers of Bendix Aviation Corporation in 1957 (9) and it was effectively used on an automobile engine by the Engineers of Volkswagen in 1968.

Fig. 15 shows the schematic diagram of the Volkswagen's fuel injection system (1).

The Volkswagen's electronic fuel-injection system is a pulse-timed manifold injection system. Each cylinder of the engine has its own injection valve which opens once for each revolution of the camshaft. An electric fuel pump draws fuel from the tank through a filter, and pumps it via a pressure line into the ringmain, which distributes the fuel to the electromagnetic injectors, which are connected to the ringmain via fuel distributing pipes. The pressure regulator connected to the end of the ringmain keeps the pressure applied to the injectors at 28 psi constant. From the pressure regulator, surplus fuel can flow through a second line back to the tank.

The prevailing operating conditions determine the amount of fuel to be injected into each cylinder. When a signal is received from the electronic control unit, the injectors are electromagnetically opened $\frac{1}{12000}$th of an inch to squirt fuel into the area above the intake valve, where it is atomized by the air rushing into the combustion chamber. The injectors are operated in

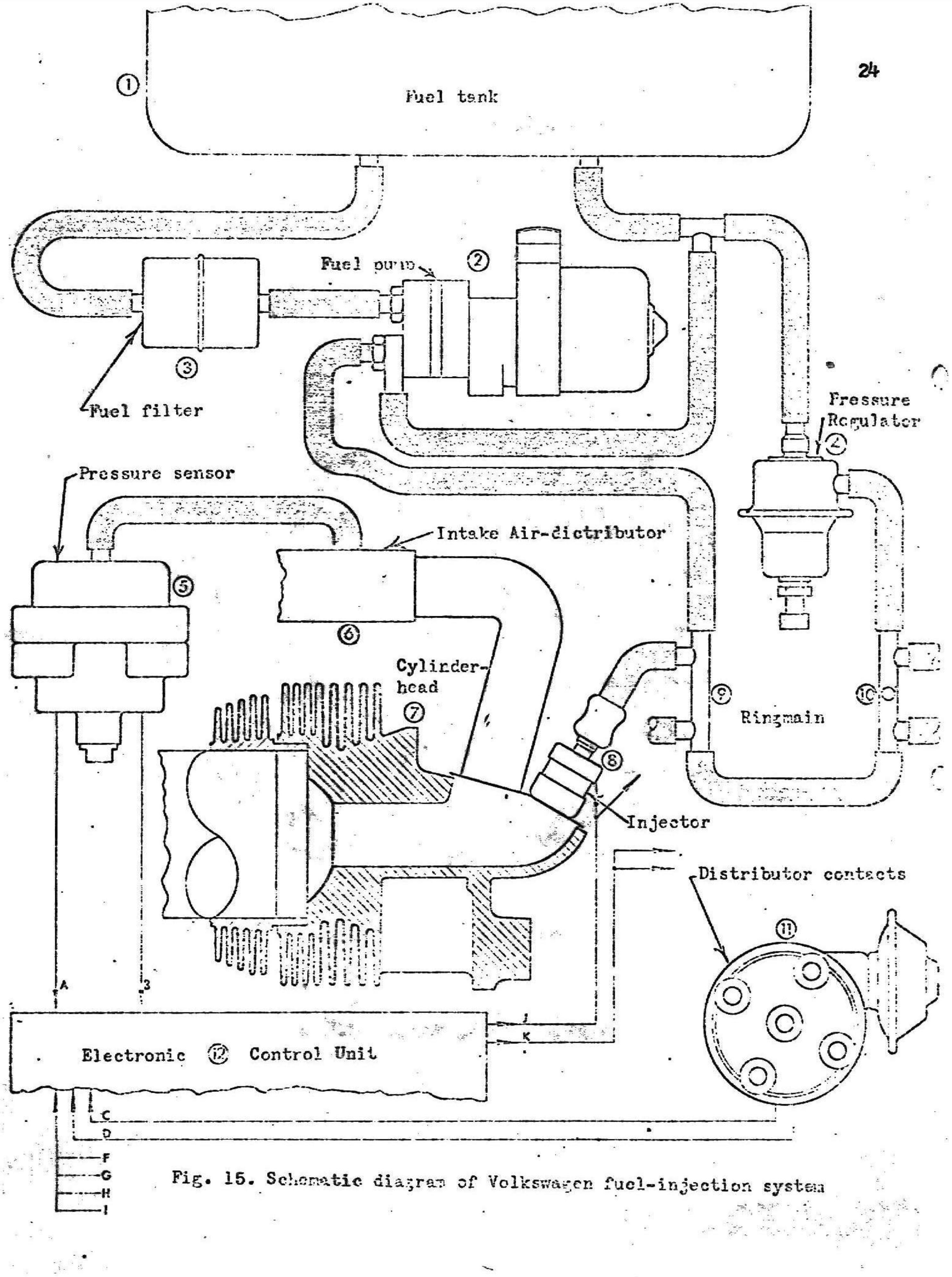

Fig. 15. Schematic diagram of Volkswagen fuel-injection system

two pairs, injector pair I = cylinders 1 and 4, injector pair II = cylinders 2 and 3.

The injector jet is accurately calibrated. For this reason and because the fuel pressure is kept constant, the amount of fuel injected depends only on the length of time the injector is kept open.

The length of time for which injectors should be kept open is computed by the electronic control unit. The information processed by the electronics in the control unit comes from the individual sensors on the engine.

A pulse generator in the distributor measures the angular position of the crankshaft to determine injection timing, which is held constant at 15 degrees after top dead centre under all operating conditions.

The injection duration is governed by the engine speed and the load condition of the engine. The engine speed is relayed to the control unit by the distributor contacts. The load condition is indicated by the intake manifold absolute pressure. A pressure sensor, connected to the intake air-distributor by a rubber hose, detects the intake pressure which is relayed to the electronic control unit.

The electronic control unit processes this information and gives a signal for the injectors to be opened for a longer or shorter period of time. The amount of fuel, governed by the engine speed and load, is called the "basic amount" of fuel.

In addition to the basic quantity of fuel, an accurately metered quantity of fuel is additionally injected when starting at outside low temperatures, when the engine is warming up, and at full throttle.

The enrichment of the air/fuel mixture for starting is dependent on the engine temperature, which is measured by two temperature sensors, one in the crankcase and another on the cylinder head. These sensors contain temperature sensitive resistors. When the cold engine is started, the fuel-air mixture is the function of temperature signal and a voltage signal from the starter. This information is processed by the control unit in relation to the basic fuel quantity and the impulses are relayed to the fuel injectors.

A signal for the enrichment of the air/fuel mixture at full throttle is relayed by the pressure switch which is operated according to the difference in the pressure in intake air-distributor and the atmospheric pressure.

On the deceleration, fuel supply is completely shut off. This operation is initiated by a throttle valve switch mounted on the air-valve body. This throttle valve switch relays the signal to the electronic control unit to suppress the injection pulses.

Air system of electronic fuel injection system

The schematic diagram of the air system is shown in Fig. 16. Four intake manifolds are connected to an intake air distributor. Clean air is supplied to the intake air distributor through an air cleaner. A throttle valve, located on the inlet side of the intake air distributor, controls the amount of air flowing into the engine. The throttle valve is connected to the accelerator pedal by a cable (1).

When idling, the throttle valve is completely closed, and air passes through a bypass system in the intake air distributor. When the engine is up to operating temperature, an idling air adjusting screw controls the amount of air necessary for the engine. At engine temperatures below 120°F, air required for smooth idling is increased, which is controlled by the auxilliary air regulator (rotary valve). It alters the functional cross-section of the