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EFFECT OF AIR-FUEL RATIO ON DETONATION IN GASOLINE ENGINES

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The richness of the mixture has a very pronounced effect on the detonation in a gasoline engine. It is known that a rich mixture tends to suppress detonation. At the time of take-off of an airplane, for example, when the power is increased and the wind velocity is rather low the engine is regulated for a very rich mixture for the purpose of preventing detonation.

The study of this effect of the mixture strength on detonation may be divided into two parts, namely: A, the measurement of the effect in engines; and B, the explanation of the effect. Although many of the considerations brought out in this paper have more or less been treated by other investigators, the author has considered it of some interest to give a brief account of this aspect of the very important problem of detonation in gasoline engines.

A. MEASUREMENT OF THE EFFECT OF AIR-FUEL RATIO ON DETONATION IN GASOLINE ENGINES

One of the methods of measuring this effect in engines consists in determining under well-established operating conditions, the allowable power as a function of the fuel-air ratio, where the allowable power is defined as that corresponding to a slight detonation. Figure 1 shows this relation for a C.F.R. engine. The allowable power is expressed in terms of mean effective pressure and the richness of the mixture is defined by the ratio: measured fuel-air ratio/theoretical fuel-air ratio for complete combustion. A richness of 1.1, for example, denotes a mixture which contains 10 percent fuel in addition to that

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*"Influence de la richesse du mélange sur la détonation dans les moteurs a essence." Congrès Mondial du Pétrole, Paris, June 1937.

which is necessary for theoretically complete combustion. (For mixtures richer than that which produces theoretically complete combustion ("correct" mixture) there exists a linear relation between the specific fuel consumption and the air-fuel ratio. For leaner mixtures this is no longer true.) Figure 1 shows the existence of a minimum allowable power corresponding to a maximum tendency to detonate at an air-fuel ratio which is practically the correct one. The tendency to detonate decreases if the mixture is made either richer or leaner. It is also seen that at a richness of about 0.9 there is attained the minimum fuel consumption. In regulating for a still poorer mixture the fuel consumption increases as a result of the slowness of the combustion.

Figure 2 shows similar curves for a single-cylinder airplane test engine. Although, in general, there appears to be agreement between the shapes of the curves for the two engines, it should be noted that in an airplane-engine cylinder the effect of the richness on the admissible power is much greater than it is on the C.F.R. engine under the conditions assumed. The heat load, which is much greater in an airplane-engine cylinder, may be an explanation of this fact.

Another method of measuring the effect of the mixture strength on detonation in engines, consists in investigating, under definite engine-operating conditions, the allowable compression ratio as a function of the mixture strength - this compression ratio being defined as that required to bring about a slight detonation. It is evident that this method requires an engine with variable compression. Figure 3 shows the results of such measurement on a C.F.R. engine (curve a). In agreement with figure 1, the maximum tendency to detonate corresponds nearly to the correct mixture. With a richer, as well as with a leaner mixture, there is a decreased tendency to detonate. For the purpose of expressing this decrease in terms of octane number, curve b has been determined which gives the relation between the antidetonating value or octane number and the compression ratio producing a slight detonation. From curves a and b was obtained curve c, giving the relation between the octane number and the mixture strength.

B. EXPLANATION OF THE EFFECT OF AIR-FUEL RATIO ON DETONATION

The effect of the mixture strength on the detonating tendency appears to be a very complicated phenomenon. Two chief aspects of the problem should be distinguished:

a) The effect of the richness on the conditions of pressure, temperature, and time during which the "endgas" or unburned portion of the charge is subjected to these conditions before autoignition is produced. These conditions, in their turn, appear to have a strong effect on the tendency to detonate.

b) The direct effect of the air-fuel ratio on the tendency of the "endgas" to autoignite.

We shall now consider the effect of these different factors under a).

I. RATIO OF SPECIFIC HEATS

The "endgas", forming the unburned portion of the charge, is subject to compression by the piston and by the expansion of the burned gases during the combustion. Now with an increase in the mixture richness there is a decrease in the specific heat ratio (k) because this value is less for hydrocarbon vapors than for air. Therefore, for the same compression ratio and mixture temperature, the pressure and temperature of compression are lower for a rich, than for a lean mixture. Thus the lower value of k tends to prevent the tendency to detonate. Figure 4 shows the relation between the richness of the mixture and the ratio of specific heats as calculated by Pye (reference 1). On the same figure are indicated the theoretical pressure and temperature of the unburned charge calculated from the values of k taken from curve a, assuming that the "endgas" is successively compressed adiabatically and assuming furthermore a piston compression ratio of 6/1 and a compression ratio of combustion of 3/1, the total compression ratio thus being 18/1. The effect of the air-fuel ratio on these values is clearly brought out. An increase, for example, in the richness, from 1.0 to 1.3 brings about a lowering of 1.6 kg/cm² (22.75 lb./sq.in.) in pressure of "endgas", and of 35° C. in temperature at the end of total compression.

II. HEAT OF VAPORIZATION

In the preceding discussion the mixtures were assumed to be dry and at the same initial temperatures. In practice, however, the heat of vaporization of the added fuel leads to a lowering of the temperature of the mixture. In order to determine the importance of this effect, there was obtained on a single-cylinder airplane test engine the relation between the temperature of the intake air, the specific fuel consumption, and the richness of the mixture for constant power and slight detonation. Figure 5 shows that a richer mixture permits a higher temperature of the intake air. For an increase in richness from 1.0 to 1.1, for example, the specific fuel consumption increases from 206 g/hp.-hr. (0.454 lb./hp.-hr.) to 226 g/hp.-hr. (0.498 lb./hp.-hr.), and the permissible intake-air temperature from 34° to 50° before detonation begins. Computation shows that the increment of 20 g/hp.-hr. (0.044 lb./hp.-hr.) does not lower the temperature of the mixture by more than 2.2° C., which would explain an increase of the same order in the admissible temperature of the intake air instead of the 16° C. actually realized. Clearly, then, the effect of increased richness on the detonation can in no way be explained by the corresponding lowering in temperature of the mixture.

III. SPEED OF FLAME

As the unburned charge is more or less rapidly compressed by the flame, the charge seeks to give up its heat to the combustion-chamber walls. The compression and the speed of cooling of both depend on the mixture strength as we shall see below. Figure 6 shows the relation existing between the richness and the mean speed of the flame front as measured from flame photographs obtained on an engine with a window in the combustion chamber (reference 2). The marked effect of the richness is evident. The speed of the flame front appears to attain its maximum for a fuel-air ratio of about 1.2, decreasing rapidly for a richer or leaner mixture. A difference, for example, of 0.2 in the fuel-air ratio produces a change in the flame-front speed of about 20 percent.

The effect of flame-front speed on detonation is rather complicated. A high flame speed indicates that the unburned charge has only a short time in which to cool through contact with the wall of the combustion chamber, thus promoting detonation. A low flame speed brings about a longer delay during which the unburned charge can cool on contact with the combustion-chamber walls, thereby retarding detonation. Account must also be taken of the fact, however, that in the case of high flame speed the unburned charge has only a short reaction time available - a fact which retards detonation whereas for low flame speed there is more time available, thereby increasing the tendency to detonation. The time factor is, in our opinion, a very important one. We have often found that, in compressing a combustible mixture without passing the spark, autoignition did not occur before an angle of rotation had been attained of 90° to 120° from the top dead center, and thus a long time after the instant of maximum pressure and temperature. Since the two effects tend to offset each other, it is necessary to investigate further as to which of these predominates.

IV. TEMPERATURE OF THE COMBUSTION-CHAMBER WALL

It is known that in regulating for a richer mixture the temperature of the combustion-chamber wall decreases - a fact which is explained by a change in the flame temperature with fuel-air ratio. Figure 7 shows the flame temperatures according to the calculations of Tizard and Pye (reference 3). (The considerable effect of dissociation is clearly evident.) It is seen that the flame temperature attains its maximum for richness between 1.1 and 1.2, and that it decreases when the mixture is either richer or leaner. Although the curve is valid for only benzene-air mixtures, its general shape remains the same for other hydrocarbons. (In this connection, it is interesting to recall that in spite of the lower combustion temperature in the case of the richer mixture, the combustion pressure does not decrease. The explanation is to be found in the fact that the "volume ratio" - that is, the number of molecules after combustion, divided by the number of molecules before combustion, increases as the mixture is made richer.)

Figures 8 and 9 show, respectively, for an air-cooled airplane engine and a C.F.R. engine, the relation between the temperature of the cylinder head and the mixture regulation. In the two engines the temperature has been measured at the lower rim of the spark plug flush with the combustion-chamber surface (reference 4). In order to determine to what extent this lowering of the temperature of the cylinder head, which facilitates cooling of the charge, contributes to a decrease in the detonation, a test was conducted on a C.F.R. engine. The engine was provided with a special cooling system which permitted the cooling liquid temperature to be varied at will between 50° and 160° C. The cooling liquid was circulated by a pump. The difference between the inlet and outlet temperatures did not exceed 3° C. and the temperature of the cooling liquid was considered to be uniform for the entire cooling system.

First, without modifying the temperature regulation of the cooling liquid, there was determined the relation between the cooling liquid temperature and the richness of the mixture, the former furnishing an indication of the mean temperature of the combustion-chamber wall. In these tests the compression ratio was determined so as to obtain a slight detonation at the point P where the temperature of the cooling liquid attained its maximum (curve a, fig. 10). The richness was then varied and the temperature of the cooling liquid regulated so as to obtain again a slight detonation for the other mixture strengths (curve b). It was then observed that for mixture strengths other than that of P the temperature of the cooling liquid, and hence the mean cylinder-wall temperature, could be higher than for the point P before a slight detonation was produced. This observation permitted the conclusion to be drawn that the decrease in temperature resulting from a greater richness of the mixture can only explain a small part of the retarding effect on the detonation.

It must, however, be pointed out that the temperature of the exhaust valve which forms part of the combustion-chamber wall, depends very much more on the flame temperature than on that of the cooling liquid. It may be explained that with a rich mixture and a raised temperature of the cooling liquid (point Q, for example), the engine has the same tendency to detonate as with a normal mixture and low cooling liquid temperature (point P, for example). As a matter of fact, in spite of the raised temperature of the cooling liquid in the first case, the temperature of the exhaust valve is still lower in the second case because of the lower flame temperature. Figure 11 shows the effect of the mixture richness on the cylinder and exhaust valve temperature as measured on the Ricardo engine E.35. It is seen that increasing the richness by 0.1 above 1.1, leads to a lowering of about 30° C. in the temperature of the exhaust valve. In varying the cooling liquid temperature from 58° to 96° C., only a slight variation will be produced in the valve temperature. The temperature plug shows a difference of nearly 20° C. Investigations are, at the present time, being conducted to determine the effect of the exhaust-valve temperature on the tendency to detonate.

It is interesting to note that the maximum values of the exhaust and exhaust-valve temperatures correspond to the richness permitting a maximum tendency to detonate (approximately 1.05) - a fact which proves a close relation between the valve temperature and the detonation tendency. The fact that the maximum exhaust temperature is obtained with a less rich mixture than that corresponding to the maximum flame temperature (about 1.15), may be explained by the lower combustion rate of the poorer mixture.

Proceeding in the same manner as for curve c in figure 3, there has been derived curve d (fig. 10), which indicates the relation between the richness and the octane number. Comparison with curve c of figure 3, shows satisfactory agreement.

From the above discussion it may be concluded that the conditions to which the unburned charge is submitted during compression by the flame vary in the following manner as the richness of the mixture is increased above that permitting a maximum tendency to detonate.

1. The pressure and temperature at the end of compression of the unburned charge decrease as a result of the decrease in the ratio of specific heats.

2. The temperature of the mixture decreases as a result of the heat of vaporization of the additional amount of fuel.

3. The duration of the compression of the unburned charge increases as a result of the decrease in the flame front speed.

4. The mean wall temperature of the combustion chamber decreases on account of the lower flame temperature. The temperature of the exhaust valve decreases by a relatively large amount.

Direct Effect of the Richness of the Mixture on the Tendency to Autoignition Independently of the Effect of the Variable Factors Mentioned Under a)

In order to study this effect, the compression ratio above which autoignition occurred as a function of the mixture strength was determined in a C.F.R. engine, the engine being brought up to steady conditions with an electric motor. The temperature of the cooling liquid was maintained constant with the aid of an electric heater in the cooling circuit. In order to eliminate any effect of the heat of vaporization, the temperature of the mixture was maintained at 150° C. for all the mixtures whose temperature assured their dryness. During the tests the weights of air and of fuel were measured for different mixture strengths. The results are shown on figure 12.

It is interesting to note that without the spark the minimum value of the admissible compression ratio giving the maximum tendency to autoignition, corresponds to a mixture richness of about 1.6 (curve b), whereas with the spark the maximum tendency to detonate corresponds approximately to the correct mixture for the same fuel (curve a from fig. 3). From this fact it could be concluded that for a given fuel-air mixture the detonating tendency in an engine is not equal to the autoignition tendency of the unburned charge. An increase in the richness of the mixture, for example, for 1.1 to 1.6, reduces the tendency to detonate in the engine, whereas the same change in the richness appears to increase the tendency to autoignition. It could thus be concluded that the richness of the mixture, by its effect on the conditions to which the unburned charge is subjected, exerts an indirect effect on the autoignition of the charge, and this indirect effect appears to predominate over the direct effect in producing autoignition.

CONCLUDING REMARKS

Considering the various aspects of the question of the effect of mixture strength on the detonation, one is struck by the complexity of the problem. The contribution made in this paper does not, therefore, pretend to completeness, but is only an attempt to present a general view of the factors involved. Many investigations will have to be conducted before all of the elements and their effects that enter into the problem, will be accurately known.

In conclusion, the author desires to express his appreciation to M. Boerlage, Director of the Delft Laboratory, as well as to his colleagues for the encouragement and effective aid they have given in the preparation of this study.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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FIGURE LEGENDS

Figure 1.- Allowable mean effective pressure and specific fuel consumption as functions of the mixture strength. Supercharged C.F.R. engine. Compression ratio 5:1. Engine speed, 900 r.p.m. Temperature of intake air, about 40° C. 77 octane fuel.

Figure 2.- Allowable mean effective pressure and specific fuel consumption as functions of the mixture strength. Single-cylinder airplane test engine. Compression ratio 7:1. Engine speed, 2,250 r.p.m. Temperature of intake air, 100° C. 77 octane fuel.

Figure 3.- Curve a: Relation between allowable compression ratio and mixture strength.
Curve b: Relation between allowable compression ratio and A.S.T.M. octane number (C.F.R. octane number).
Curve c: Obtained from a and b and showing mixture richness expressed in A.S.T.M. octane number.
C.F.R. engine with special camshaft. Engine speed, 900 r.p.m. Temperature of mixture, 150° C. 66 octane fuel.

Figure 4.- Specific heat ratio as a function of the mixture strength according to Pye (reference 1). Theoretical pressure and temperature of the unburned charge at end of compression calculated by above relation, assuming a piston compression ratio of 6:1 and a flame compression ratio of 3:1, making a total compression ratio of 18:1. Pressure before compression, 1 kg/cm^2; initial temperature, 100° C.

Figure 5.- Allowable temperature of intake air and fuel consumption as functions of mixture strength. Single-cylinder air-cooled engine. Compression ratio 7:1. Engine speed, 2,250 r.p.m. Constant mean effective pressure, 7.9 kg/cm^2.

Figure 6.- Speed of flame front as a function of the mixture strength as measured in an engine with a window in the combustion chamber (reference 2). Engine speed, 700 r.p.m.

Figure 7.- Computed flame temperature as a function of the mixture strength, according to Tizard and Pye (reference 3).

Figure 8.- Effect of mixture strength on temperature measured at rim of spark plug flush with combustion-chamber wall (reference 4). No detonation. Single-cylinder air-cooled airplane engine. Compression ratio, 7:1. Engine speed, 2,250 r.p.m. Temperature of intake air, 60° C.

Figure 9.- Effect of mixture strength on temperature measured at rim of spark plug (reference 4), specific fuel consumption and mean effective pressure. C.F.R. engine with special camshaft and modified carburetor. Compression ratio, 6:1. Engine speed, 1,100 r.p.m. Temperature of mixture, 100° C.

Figure 10.- Curve a: Relation between temperature of cooling liquid and mixture strength. Slight detonation at point A.
Curve b: Relation between allowable temperature of cooling liquid and mixture strength.
Curve c: Relation between allowable temperature of cooling liquid and A.S.T.M. octane number.
Curve d: Effect of mixture strength expressed in terms of A.S.T.M. octane number. (See also fig. 3.)
C.F.R. engine with special camshaft and usual carburetor. Engine speed, 900 r.p.m. Compression ratio, 4.2:1. Temperature of mixture, 100° C. 66 octane fuel.

Figure 11.- Temperature at the exhaust, of the exhaust valve, of the temperature plug, and mean effective pressure as functions of the mixture strength. Ricardo E.35 engine. Compression ratio, 5.9:1. Engine speed, 1,500 r.p.m. Temperature of mixture, 30° C. Ignition advance, 38°. 87 octane fuel. No detonation.

Figure 12.- Relation between allowable compression ratio and mixture strength with and without passage of spark for same fuel. C.F.R. engine with special camshaft. Engine speed, 900 r.p.m. Cooling liquid temperature maintained constant at 100° C. Mixture temperature maintained at 150° C. 66 octane fuel.

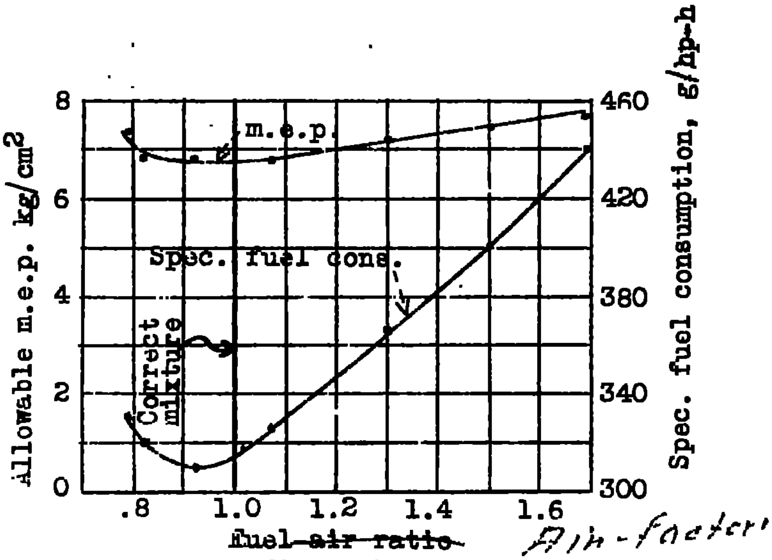


Figure 1.

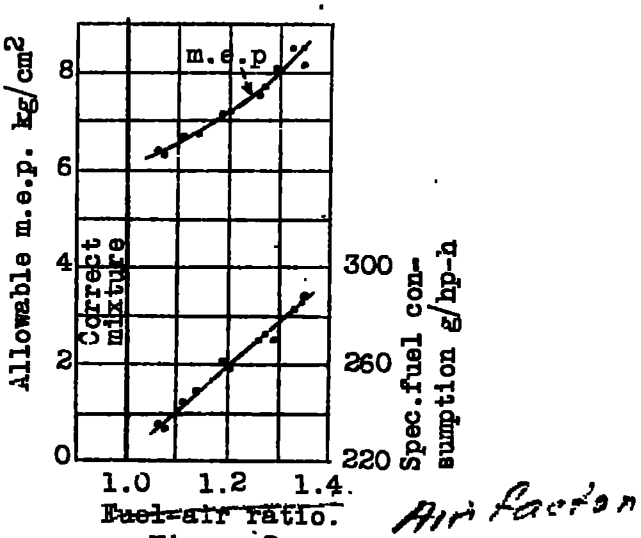


Figure 2.

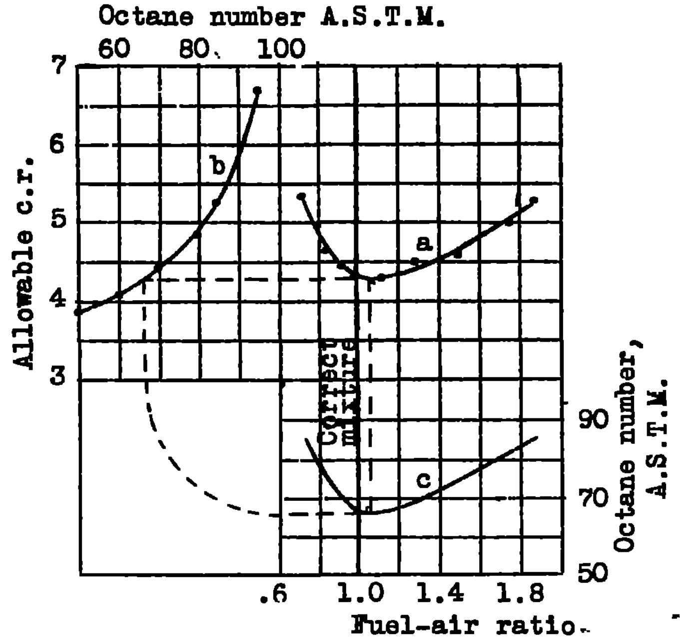


Figure 3.

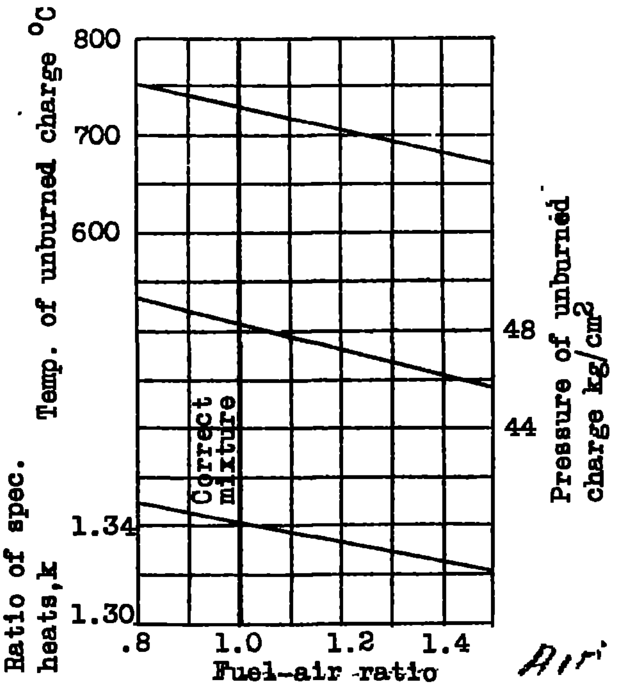


Figure 4.

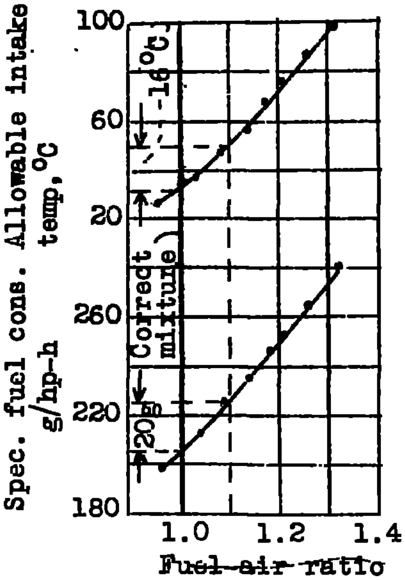


Figure 5.

Air Ratio

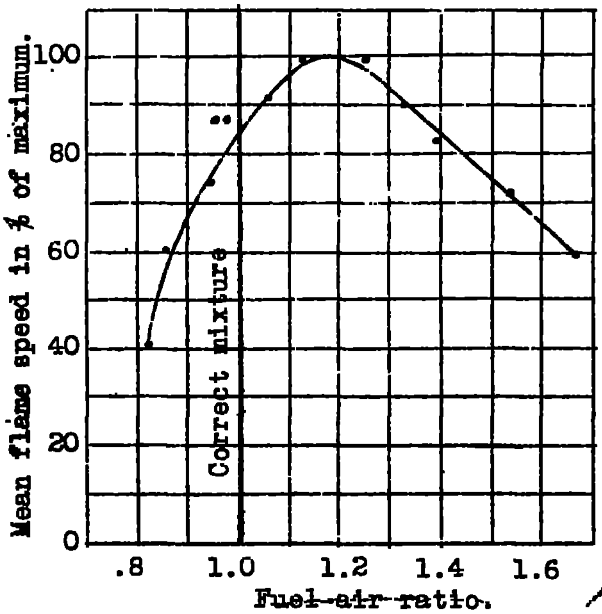


Figure 6.

Air Factor

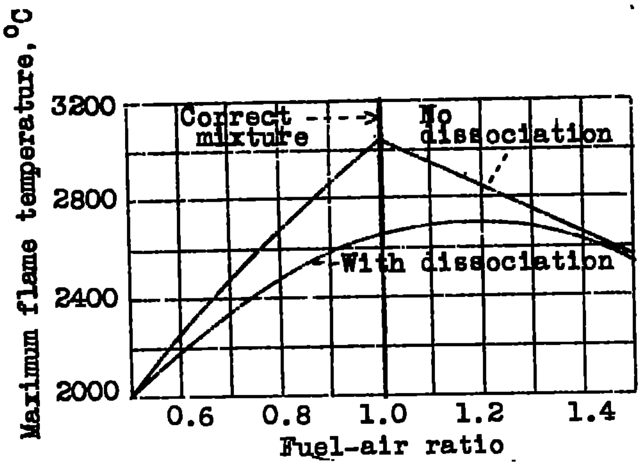


Figure 7.

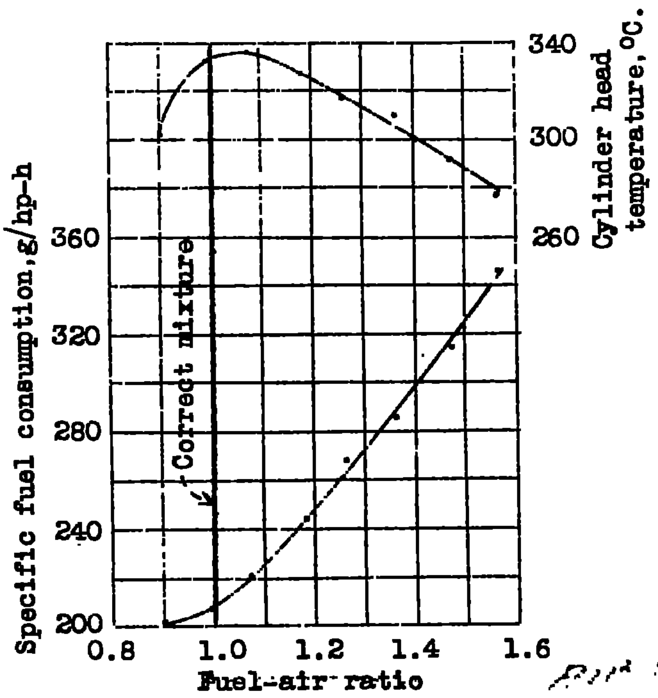


Figure 8.

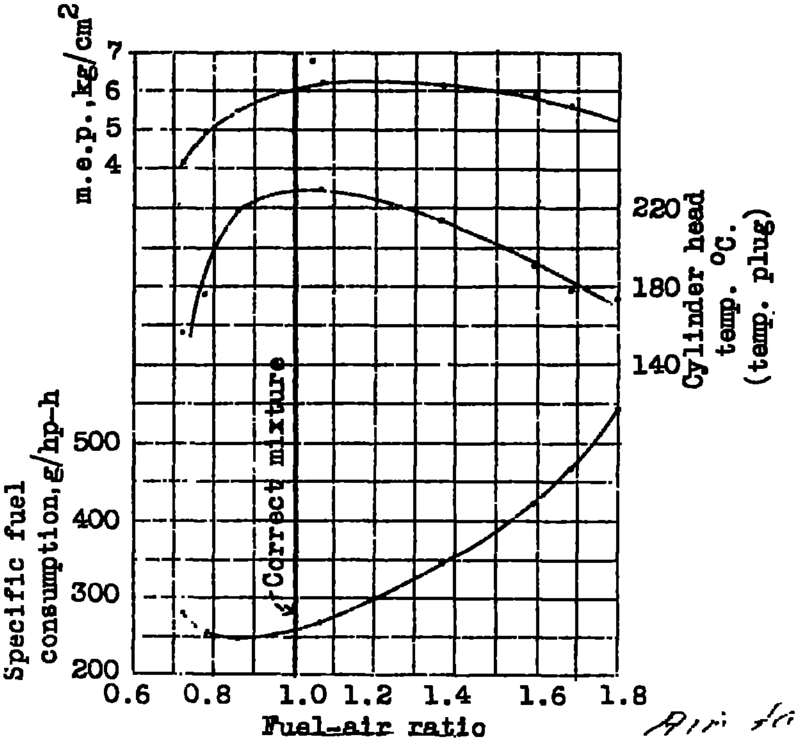


Figure 9

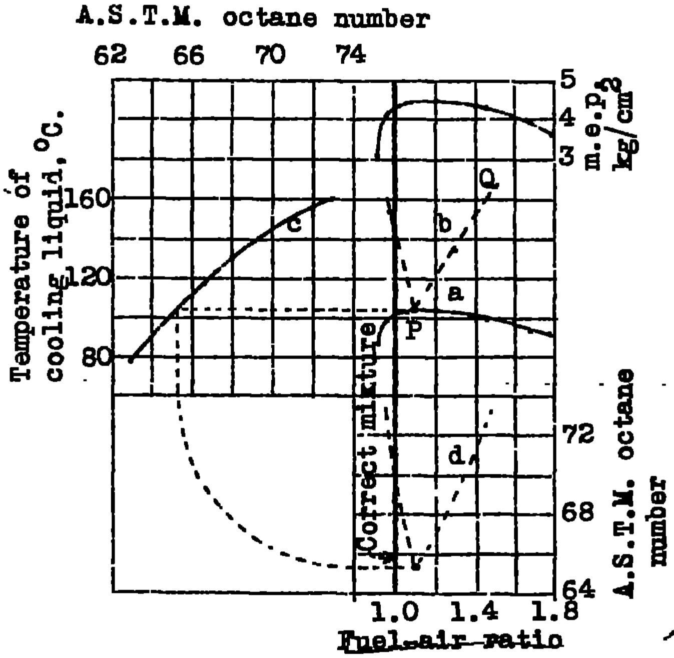
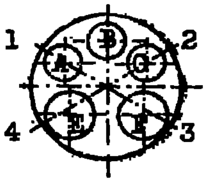


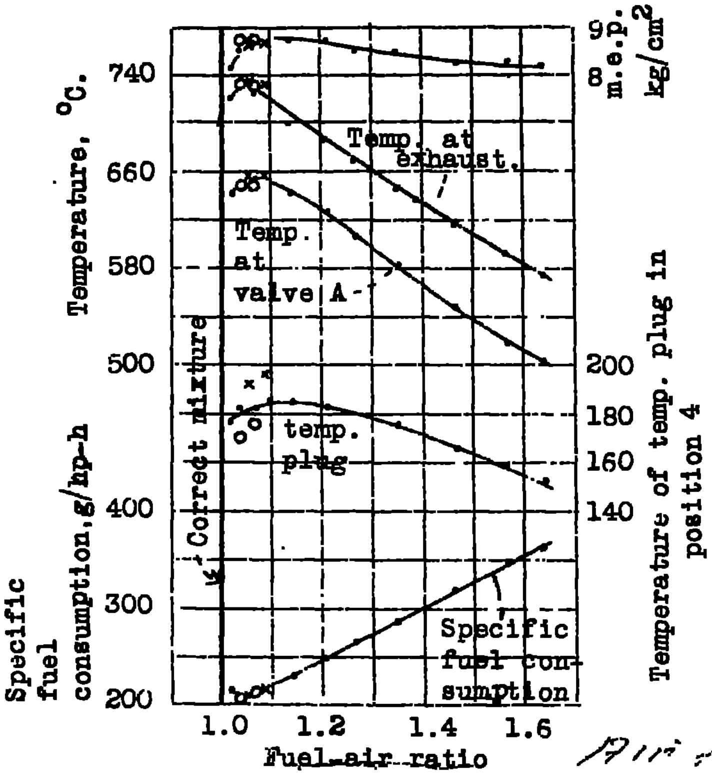
Figure 10

Temperature of cooling liquid

Curves —— 68 °C.
Points × 96 °C.
Points ○ 58 °C.

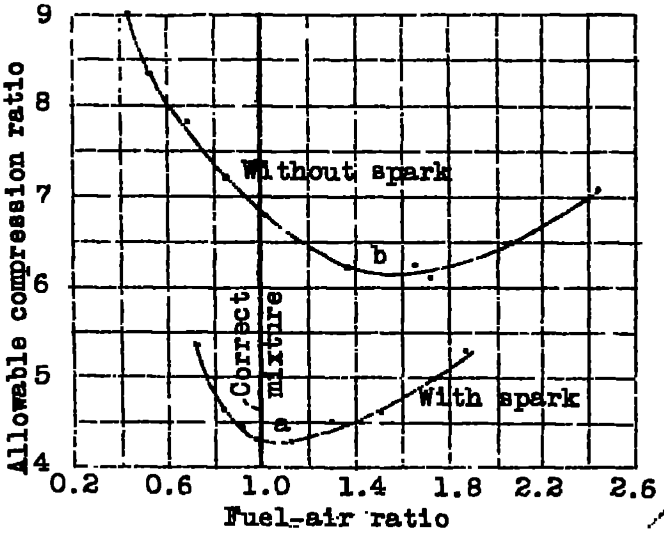


Exhaust valves A,B and C
Intake " E " F
Plugs in positions 1 and 3



Air factor

Figure 11.



Air factor

Figure 12.