TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 149

INFLUENCES IN THE SELECTION OF A CYCLE FOR SMALL HIGH SPEEDENGINES RUNNING ON SOLID OR AIRLESS INJECTION WITH COMPRESSION IGNITION.

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INFLUENCES IN THE SELECTION OF A CYCLE FOR SMALL HIGH SPEED ENGINES RUNNING ON SOLID OR AIRLESS INJECTION WITH COMPRESSION IGNITION.

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What cycle of heat phases should be selected for small high speed* engines running on solid or airless injection with compression ignition, and what should be the relative proportions of these heat phases?

In undertaking to answer these questions the following items have been taken as limiting conditions in determining the form of the pressure volume diagram.

(a) Indicated mean effective pressure,

(b) Fuel economy,

(c) Permissible maximum pressure.

With limits set to those quantities, a cycle of heat phases can be laid down. This chosen cycle may, however, remain but a choice. To obtain it in practice is another matter. This is because the cycle as laid down on paper does not reveal the limitations to combustion control with high R.P.M.

Hence before proceeding to lay down a series of heat phases to meet chosen conditions of M.E.P., fuel economy, and maximum pressure, the question of the feasibility of combustion control

*By high speed engines is here meant those having the R.P.M. of four-stroke airplane and automobile engines.

under the conditions of the desired R.P.M. and with the existing knowledge of fuel combustion and solid injection phenomena, will be considered.

Since a significant amount of constant pressure combustion is not only desirable but, for airplane engines at least, an essential, as later discussion will show, it seems safe to say at the present time that to undertake the selection of a definite heat cycle for small engines, running on solid or airless injection and compression ignition, with insistance on fixed proportions for the extent of the combustion lines, is a step ahead of practical achievement. For the problem of operating a small high speed engine on a desired cycle differs widely from that for the large stationary or marine engine; and the discrepancies between what proportions for the heat phases are desirable and what are attainable, seem likely to tax engineering thought for some time when using the higher airplane and automobile engine speeds.

The obstacles seem to lie with fuel characteristics and the time available for the progress of the heat phases, rather than purely mechanical operations. It takes time for fuel to evaporate. Without evaporation, or else a chemical change, no combustible mixture of fuel and air occurs. To obtain this necessary evaporation interval the fuel must be injected early. Injecting fuel early in a high speed engine means some number of degrees of crank travel in advance of the beginning of combustion as laid down on the chosen diagram of heat phases. Compared with stationary engine practice, this number of degrees of advance for the high speed engine, will exceed stationary engine practice in proportion to the increase in R.P.M. Thus with injection beginning 10° before dead center for an engine running at 400 R.P.M. there should be 40° advance at 1600 R.P.M. in order to give the same interval before dead center in terms of fractions of a second. Further, the allowable interval during which combustion must be completed will be, in seconds, only one-fourth as long. Hence the evaporation of a greater proportion of the fuel charge must occur before dead center in order to give the fuel access to oxygen and make combustion complete without late burning. And what follows?

The higher the R.P.M. the earlier, in terms of crank travel, the injection must occur, with preignition as the limit. The higher the M.E.P. the more fuel must be injected before dead center. This last condition is the opposite of that which gives the excellent operation and economy of Diesel engines; and the result is high maximum pressures, which can, within limits, give high economy. Combustion, however, is liable to be too rapid to permit uniform and continuous running except with low M.E.P.

Further research on combustion and fuel evaporization phenomena, may lead to better understanding of the persistence of the peak pressure in even relatively low speed solid injection engines. Already it is known that an increase in temperature accelerates combustion enormously. Also an increase in pressure without an increase in tempreature induces self-ignition. Both of these conditions tend to foil the attainment of constant pressure combustion so long as early injection is necessary. Fuel injected before dead center in excess of that to give the chosen amount of constant volume combustion, tends to rush into further constant volume combustion. For at high R.P.M. ignition must occur well in advance of dead center. But with compression ignition the pressure at ignition is already as high as the maximum pressure often obtained when running on carbureter. Hence the initial combustion under the accelerating influences of the temperatures and pressures from that combustion, as well as from further adiabatic compression, becomes extremely rapid combustion, and the premature burning occurs of fuel intended for supporting combustion after dead center. The ready division of all the combustion into chosen portions at constant volume and at constant pressure has yet to be attained in high speed engines.

Concerning the selection of a suitable cycle neither the Otto nor the Diesel cycle meets the requirements of high capacity with high efficiency for airplane engines when operated with medium compression, solid injection and compression ignition. The fitness of using only medium compression rather than the 500 lbs. to 550 lbs. pressures of pure Diesel practice, requires no comment here. If a compression pressure of 325 lbs. absolute be chosen - sufficient to give compression ignition when running on gas oil without the aid of any auxiliary devices except when starting from cold - the M.E.P. of the conventional actual Diesel engine card, as shown in Curve 1, Fig: 4, is too low. Thus Curve 1* shows that with C.O. (cut-off) occurring when Y = 2, (Y = ratio of volume of cylinder contents at C.O. to clearance volume), the indicated M.E.P. is only 70 lb. This value of Y = 2 is common in large Diesel operation, but with regular Diesels operating on 500 lb. to 550 lb. compression pressure, the compression and expansion lines enclose more area when the same length of admission line occurs. In order to obtain an indicated M.E.P. of 125 lb. from a conventional Diesel card with compression pressure 325 lb. absolute, Y must equal 3. To get an M.E.P. of 149 lb., Y must be 3.5.

What would the fuel consumption be when Y = 3.5? It would probably not be permissible. Large Diesel engines running at only 125 R.P.M. or under, and burning only sufficient fuel to give one-half to two-thirds the M.E.P. of airplane engines, give their best fuel economies with Y under 2. Hence with Y = 3.5 and airplane engine speed and M.E.P. late burning would occur. Further, the cycle efficiency would correspond to that for 9.5 compressions instead of about 14 for the Diesels. Again the C.O. for Y = 3.5 is from the conventional actual card; the C.O. on an ideal card corresponding to the fuel supplied to give this conventional card, would be still later.

*Note: All curves of this article are based on a suction pressure of 14 lb.; 325 lb. absolute compression pressure; and an exponent of 1.4. These conditions give a compression ratio of 9.43. The Otto air card exponent of 1.4 is here used in calculating M.E.P.'s. A value more consistent with probable operations could have been taken, but in using this value some of the data can be used for comparing both M.E.P.'s and cycle efficiencies, and without falsification of the deductions.

Considering the Otto cycle and still using 325 lb. compression pressure, the indicated M.E.P. from a conventional actual engine card increases directly with the maximum pressure of this card, - i.e., with the amount of heat utilized from the fuel. The cycle efficiency, however, remains the same regardless of the amount of heat supplied per cycle so long as the compression ratio and the characteristics of specific heat for the working fluid are not changed. Here, then, it is the allowable maximum pressure that measures the fitness of the cycle. By increasing the compression pressure from Liberty engine practice (about 134 lb. absolute at sea level) to 325 lb. absolute the work of compression is increased by over 50%. Hence to obtain the Liberty M.E.P. the mean expansion pressure must be correspondingly higher than with Liberty carbureter operation. But the maximum effective pressure occurs at the beginning of the stroke when the compression pressure is also at a maximum; and in Fig. 1 shows that for a conventional Otto card with an M.E.P. of only 83.5 lb. the maximum pressure must be 800 lb. To get an M.E.P. of 119 lb., which the Liberty can exceed, the maximum pressure must reach 1000 lb., as shown on Curve 2, Fig. 4. For other than mechanical reasons such pressures are not attractive. As yet experimenters are not all agreed whether the combustion pressure or the combustion temperature may be the determining factor in creating detonation. If either opinion is correct, then whenever a high M.E.P. is attempted by means of high maximum pressures, detonation will always, at least, be near at hand in high speed engines where injection must be early. If it is attempted to avoid detonation by injecting later, then the fuel consumption is increased because of late burning. Pure constant volume combustion is, then, not permissible at high M.E.P.'s and the pure Otto cycle is eliminated.

TABLE 1.

Reduction in maximum pressure and in M.E.P. due to cutting off the peak of Otto card. The width of the peak has been made 0.2 x clearance volume.

Peak pressure in lbs./sq.in.	500	600	700	800	900	1000
Maximum pressure after rounding peak.	388	465	542	620	697	755
Per cent reduction in M.E.P.	4	3.1	2.6	2.4	2.2	2.1

Perhaps the peak may yet be controlled by doping the fuel, but the necessary dope must retard combustion without slowing up evaporation. The great reduction in peak pressure resulting from a slight rounding of the peak of the conventional card and with but small reduction in M.E.P., is shown in Table 1. This reduction in pressure and temperature should considerably increase the cylinder efficiency of the engine and also help the mechanical efficiency. Large amounts of dope would probably be required, however, with 325 lb. compression; and its possible influence in slowing up the rate of evaporation must be considered.

Fig. 3 shows a dual combustion or Sabathe cycle to give high M.E.P. under conditions that are probably all permissible in airplane engines if detonation did not follow. Just what sustained maximum pressure could be withstood is, of course, as yet problematical. The same amount of heat when supplied at constant pressure of the gases means lower temperatures than when supplied at constant volume; hence though the sustained constant pressure means increasing temperatures the gases throughout this cycle should not reach the extreme temperatures of the constant volume cycle. But the difficulty of even approximating the derived proportions for the heat phases represented by the conventional card, Fig. 3, needs little emphasis when the total time interval for all associated combustion processes is considered. Table 2 gives numerical values that reveal the severity of the time limitations placed upon the mechanical operations alone.

TABLE 2.

Crank interval in degrees	40°	70°	40°	70°	40°	70°
R. P. M.	80	80	260	260	1600	1600
Time interval in seconds	.0833	.1458	.02565	.0448	.00417	.00719

TABLE 2 cont'd

Crank interval in degrees	40^{o}	70^{o}	40^{o}	70^{o}
R. P. M.	2200	2200	3000	3000
Time interval in seconds	.00303	.0053	:00327	.00397

Besides the advantage of lower maximum pressures the dual combustion cycle has another advantage over the Otto cycle. As pointed out by Dr. W. J. Walker*, the consideration of variable specific heat would show the dual combustion cycle efficiency, for a particular value of Y, to excel the Otto cycle efficiency when both have the same compression ratio.

Summing up this analysis:

(1) To get capacity without excessive maximum pressures, some constant pressure as well as constant volume combustion is needed.

(2) To get the high M.E.P. desired for airplane engines, provision must be made for rather high maximum pressures.

(3) A division of the combustion process such that a considerable portion of the fuel will be expended in constant or approximately constant volume combustion and the remaining portion of the fuel expended in constant or approximately constant pressure combustion, appears, at the present time, to be the problem determining the attainable capacity, rather than the utilization of all available oxygen as in carburetted engines.

*"Engineering" London, April 9, 1920.

(4) Until such time as item (3) has been well solved maximum capacity will, for a chosen compression pressure, probably be governed by a permissible maximum pressure; which pressure directly as pressure concerns design, smoothness of running, durability and upkeep; and indirectly concerns those items because of the proximity of the corresponding temperatures to the detonation zone.

(5) The selection of a cycle as influenced by the possible effect upon the mechanical efficiency and cylinder efficiency (ratio of that heat actually converted into work to that theoretically made available as work by the phases of the chosen cycle) is largely bound up with item (3), which means the control of maximum temperatures and lateness of burning through mastery of the injection and combustion chamber processes.

(6) Solid injection with the retention of spark ignition would eliminate much difficulty in attaining high M.E.P. with low maximum pressures. But this would be an evasion of the heavy fuel problem.

(7) The most formidable item in the entire problem, so long as high M.E.P. is required, is the shortness of the time interval.

In placing judgement upon the difficulties shown in this analysis it should be borne in mind that formidable as is this problem, the fuel situation in the automotive industry and the value to aviation of greater safety, call for its solution

Langley Field, Va.
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Fig. 1, & 2

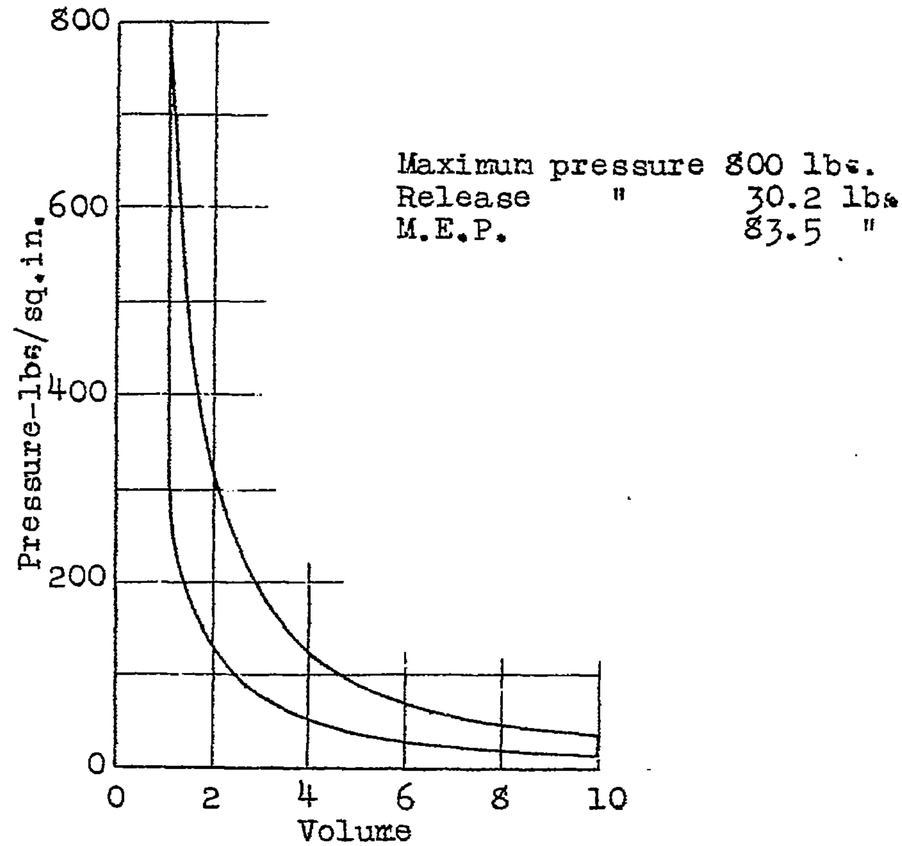

Fig. 1 Pure Otto cycle

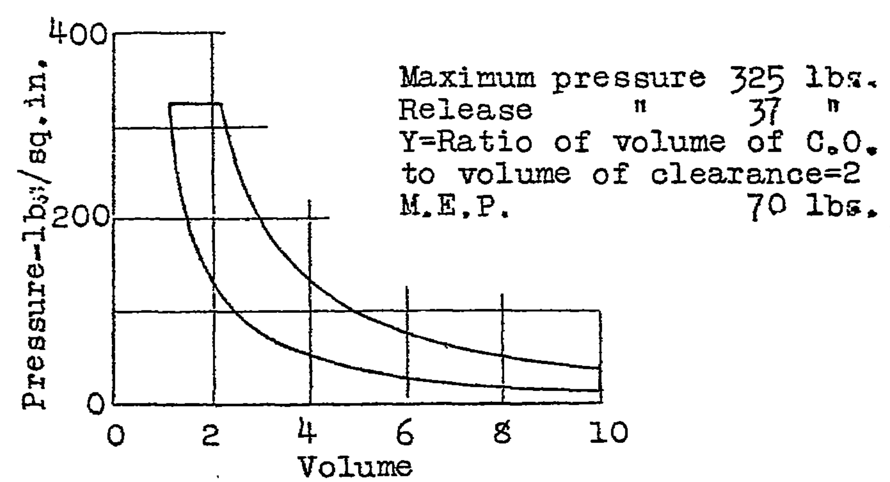

Fig. 2 Pure Diesel cycle

Fig. 3

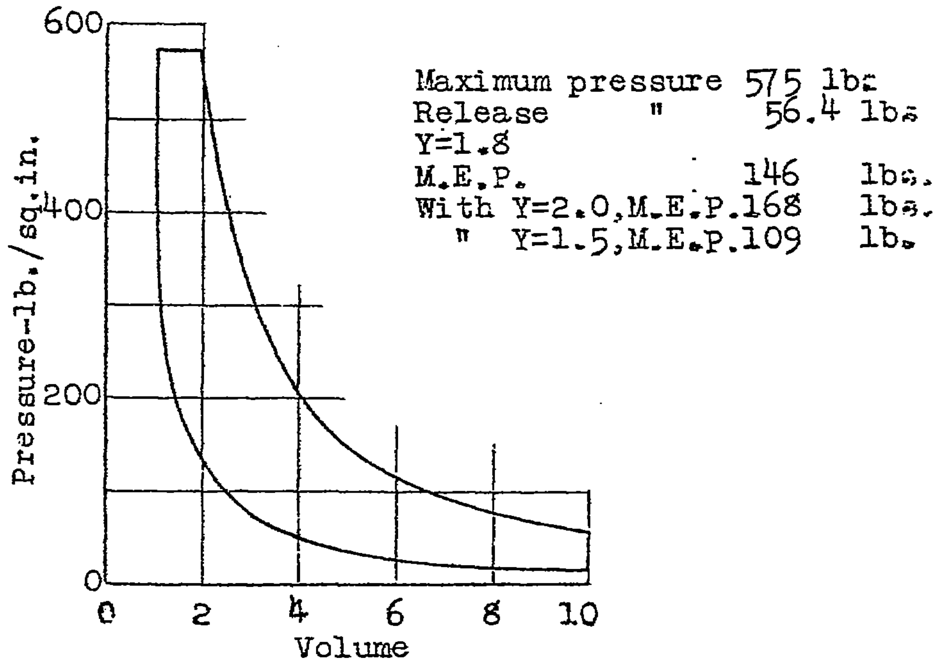

Fig. 3 Dual combustion cycle

Constants for Figs. 1, 2, & 3
Suction pressure 14 lb.
Compression pressure 325 lb.
Exponent of curves 1.4
Ratio of compression 9.43

Fig. 4

Suction pressure 14 lb.
Compression pressure 325 lb.
Exponent of curves 1.4
Ratio of compression 9.43=r

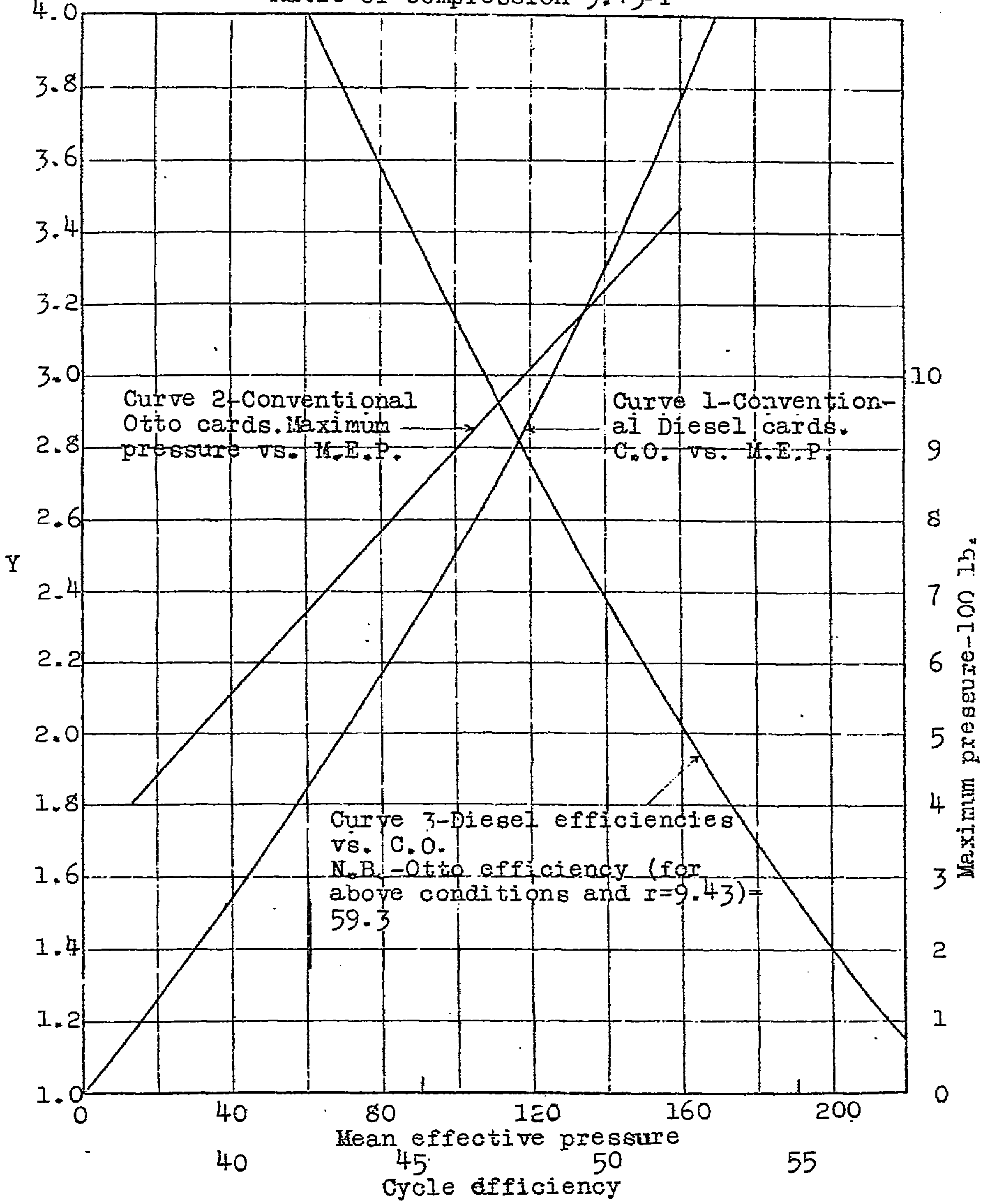

Fig. 4