

Realization of a Rapid Compression Machine (Application to the Determination of Gaseous Premixtures Autoignition)

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ABSTRACT

A Rapid Compression Machine, easy to built, adjust, use and modify had been constructed in the lab. Either with to a one stroke, compression only cycle, or a two strokes, compression/expansion cycle, it can operate in times corresponding to an engine rotating at more than 1 500 rpm. In the aim to perform rapid schlieren or shadow cinematography, it is fitted with glass cylinder head, mirror piston and, to play on the end gas temperature, with a warmed test cylinder. After explaining the principle on which the set up operates and its working designed features, we give its main characteristics, first without combustion and after with combustion cycles. By using argon as diluant, during compression only cycles without spark ignition, we set out some results connected with n-butane and iso-butane autoignition temperature and global delay versus equivalent ratio.

INTRODUCTION

Rapid Compression Machines (RMC) are very efficient devices able to reproduce, in labs, in more simple experimental conditions, a low level of gas movements, but well representative of complex phenomena which govern the combustion processes, in a spark ignition engine.

It seems the first RMC was made, as soon as the start of the century, by Falk (1), to measure the minimum ignition temperature of fuel gases. Very simple at the beginning, this kind of plant became progressively more and more complex and efficient in the course of years.

Nowadays a good deal of studies have been performed, or are always in progress, with such equipments of several different types (2). Mainly used to learn the complete evolution of spark ignited combustions they generally work in a two or four strokes cycle. On the contrary, the determination of autoignition delays requires a one stroke device, with a fast rise time. The set up built and presented here is of a new kind and allows to carry out experiments in these two ways.

In a previous article it was shown that one type of vibratoring combustions of n-butane, observed in constant volume chamber, presents the same features as those of reciprocating engine knock (3). Since the pressure and temperature of the end gas vary continuously during the ignition delay period it was impossible to measure this parameter. That is the reason why, to characterize the autoignition of n-butane and iso-butane, a new study, was undertaken in a RMC (4). It pointed out the evolution of the two-stage process delays versus the end gases temperature. Now this paper reports, for these two fuels, the autoignition time delay and temperature evolutions versus the equivalence ratio.

PRINCIPLE OF THE R.C.M.

The originality of this R.C.M., designed and built in our lab, results from its modular structure which makes it very easy to use and adapt. A one stroke type, it is built up of three main different parts, namely : the test section and the driving system, connected with the transmission cam. The set up, easily accessible, is fixed on a 2 x 1 m² stiff table, weighed down at its bottom (fig. 1).

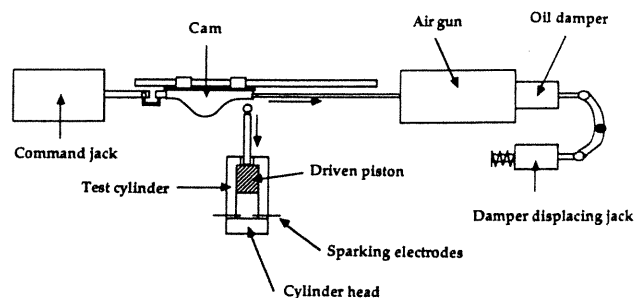


Fig. 1 Principle the machine works on.

The driving system (1- fig. 2) works as a gas gun. Its mover force comes from pressurized air, stocked in a high pressure cylindrical reservoir encircling the driving cylinder. At the beginning of its displacement, the driving piston (2), which acts as a valve, links the chamber of the driving cylinder, with the reservoir,

starting its own rapid motion, by means of a connecting rod (4). Through its motion, this piston hauls, in translation, the trolley of the linking cam (5). The latter pushes the driven piston stem (6), in the test cylinder, perpendicularly to its displacement, thereby compressing the gases, contained in the test chamber (8). Towards the end of the track a progressive oil damper (7) stops the working system. The force resulting from the increase of pressure, in the test chamber, is sufficient to limit the movement of its piston toward the cylinder head.

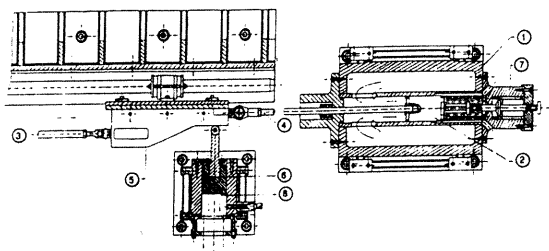


Fig. 2 Sketch of the three main parts of the machine.

An optoelectronic device together with holes, drilled in the piston rod, makes it possible to tune up ignition time versus piston position.

Depending on the cam shape used, it is possible to alter the piston movement of the test chamber and obtain either (with or without combustion) a compression only stroke, with full stop at top dead center (tdc), or a compression and expansion stroke, ending at bottom dead center (bdc).

In its present configuration, the test chamber, equipped with a 60 mm diameter piston of a 50 mm stroke, has a capacity of about 140 cm³ and a volume ratio ϵ of the order of 6.

The ignition of the premixture is obtained either by autoignition, resulting from the rise in temperature due to compression, or by a spark, triggered between two electrodes, to an adjustable point on a diameter of the chamber. The ignition energy is given either by a standard ignition system, from the car industry, or by a calibrated generator built in the lab.

During the operation, thanks to a piezoelectric probe, the evolution of the pressure, in the combustion chamber, is recorded on a numerical oscilloscope.

The use of a mirror piston with a transparent cylinder head makes it possible to perform rapid cinematographies of the flame front expansion, either with striaoscopy or shadowgraphy.

In order to play on initial temperature of fresh gases, the test cylinder can be heated with electric resistances.

CYCLES WITHOUT COMBUSTION

The first tests, performed without combustion, have made it possible to characterize the machine performances.

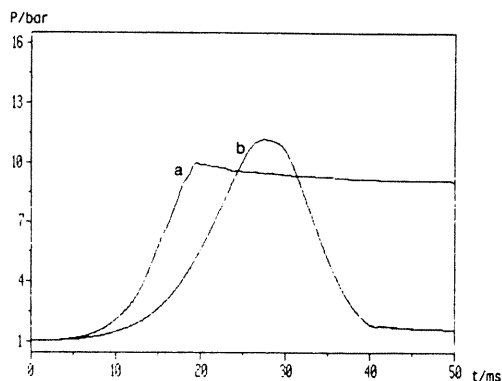


Fig. 3 Duration of a mechanical cycle :
a- Compression only.
b- Compression with expansion.

Thus it was noticed that, depending on the cam used, for a working pressure of 5 bars and an initial pressure of 1 bar, in the test chamber, the cycles duration, of compression only or compression / expansion, were respectively of the order of 15 and 25 ms, which corresponds, for an engine, to rotation speeds superior to 1500 r.m.p. (fig. 3).

The comparison between the evolution of pressure measured, after a compression only cycle, with that of a perfect gas, leads to an estimation of less than 4 % leaks, during and after piston displacement (fig. 4).

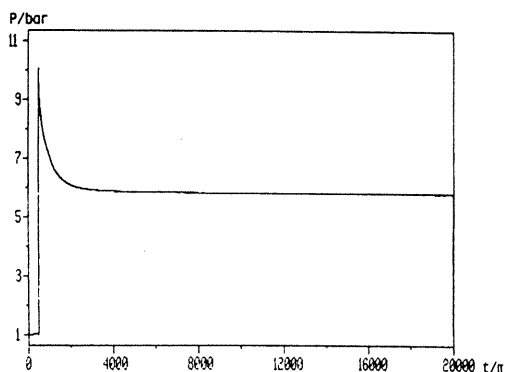


Fig. 4 Thermal leaks evaluation.

The decrease of pressure, after the stopping of piston movement at tdc, and the difference between the maximum pressure P_m measured and the value P_i given by an isentropic compression, shows that, due to important thermal losses, this transformation cannot be considered adiabatic. Under such conditions, the evaluation of gas temperature remains rather tricky.

The temperature $T_i = T_0 \cdot \epsilon^{\gamma-1}$ (where $\gamma = C_p/C_v$), calculated with the assumption of isentropic compression is too high and can only constitute the upper limit of the real value. The mean value $T_m = T_0 \cdot \epsilon \cdot P/P_0$, obtained by using the perfect gas equation, and taking into account the ratio of the initial pressure P_0 versus P really measured at the given time, is not satisfactory either, because it leaves

out the temperature gradient resulting from thermal losses. This value is too great for the gases near the walls and too small for those at the kernel. The best approximation, which we use and extend to cycles with combustion, consists in calculating the temperature $T_c = T_o \cdot \left(\frac{P}{P_o}\right)^{\frac{\gamma-1}{\gamma}}$ of the kernel only, while assuming that it is being compressed adiabatically.

SPARK IGNITED CYCLES

When testing the increase effect of initial temperature on combustion, one notices a decrease of combustion duration, due to flame speed rise (fig. 5).

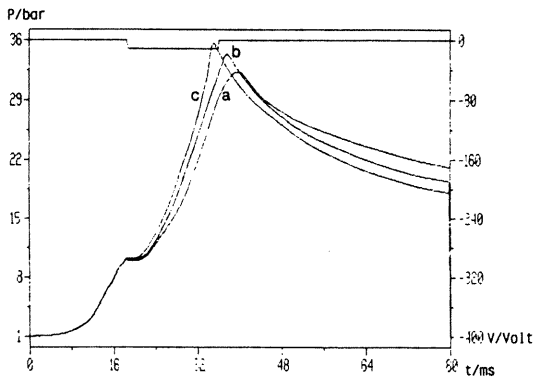


Fig. 5 Initial temperature influence on compression / combustion cycles.
a = 30° C, b = 50° C, c = 70° C.

The displacement of ignition point towards the center of the chamber, also makes it possible to reduce combustion time, therefore thermal losses, when the piston is moving, and thus to increase pressure at tdc (fig. 6).

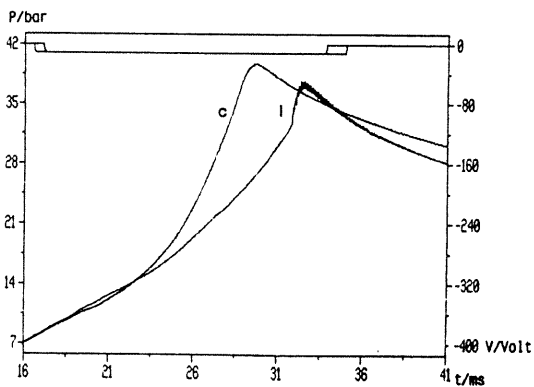


Fig. 6 Spark plug location influence, on compression / combustion cycles.
c = central, l = lateral

The effect of equivalent ratio, both on maximum pressure, reached at the end of combustion, and on combustion duration, is well displayed on the records (fig. 7).

Because of the absence of initial gas movement, combustion duration is greater than that normally observed in an engine. For a small ignition advance, this duration even becomes greater than that of the

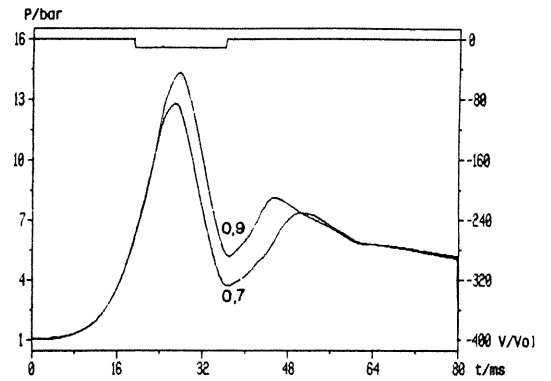


Fig. 7 Equivalence ratio influence on compression/combustion/expansion cycles.

mechanical compression/expansion cycle, inducing a first pressure peak, when the piston passes tdc, followed by a second one corresponding to the end of combustion at the bdc, i.e. with practically constant volume (fig. 8).

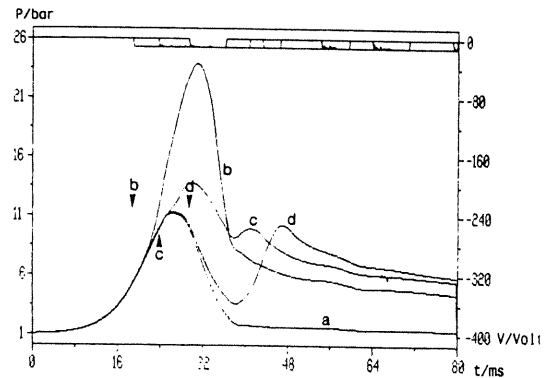


Fig. 8 Ignition time influence.
a- without ignition, b- ignition at b
c- ignition at c, d- ignition at d.

Either by increasing the initial temperature above 60° C, which induces a rise in the temperature of end gas (curve c, fig. 5), or by using lateral ignition, which enhances the combustion time (curve 1, fig. 6), we obtain vibratory combustions characterized by an acceleration of combustion.

CYCLES WITH AUTOIGNITION

After having study autoignition, in a heated constant volume combustion chamber (3), where the hot flame emission of radiations was too strong to allowed the recording of blue light, emitted by cool flames, we attempted to check and supplement these first results in a R.C.M., working in a compression only cycle, without spark ignition, where this drawback was not to be fear. We determined autoignition delays of gaseous premixtures of normal or iso-butane, because these gaseous hydrocarbones represent, in the best way, liquids fuels used in engines, and (0.21 O₂ + 0.79 A). Argon is used, insted of nitrogen, to increase γ and, in this way, the final temperature of the compressed mixture. In addition to

that, the autoignition chemical kinetics of these two fuels and especially the role of the low temperature prereactions are better understood.

Recorded simultaneously with the pressure, the light emitted by the fresh gases enabled us to check that the autoignition occurred in two steps. For the first τ_1 ms, which takes place after the piston reached tdc, it happens nothing else a small pressure decrease, due to thermal leak (fig. 9). Quite the contrary after τ_1 , a pressure step and a light peak appear simultaneously. During the following τ_2 ms, the pressure increased and the glowing go on but very weakly. Endly after this second delay, an intense light and a sudden and important increase of pressure bring out. τ_1 corresponds to the delay needed for the beginning of the first prereactions.

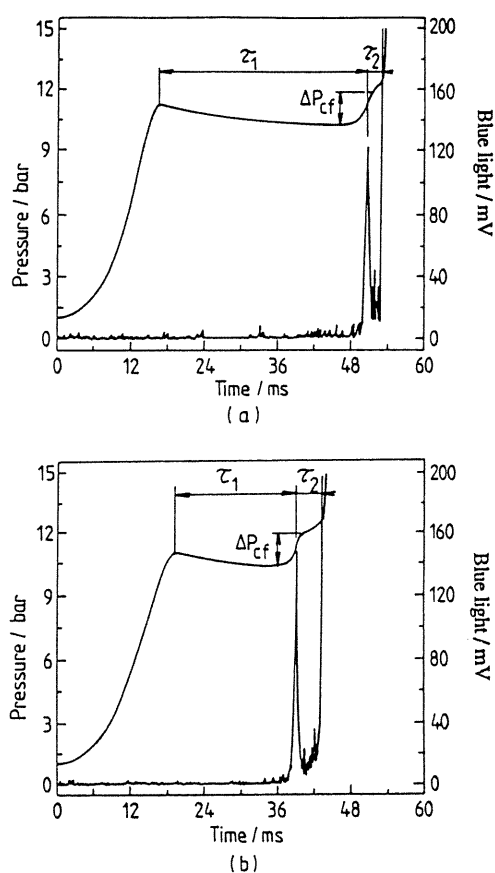


Fig. 9 Autoignition behavior of iso-butane (a) and n-butane (b).

The first delay τ_1 corresponds to the time needed for the beginning of the first pre-reactions. According to Levedahl (5) and our own previous results, during τ_2 , these pre-reactions, or cool flames, produce intermediate species, such as excited formaldehyde (6), which warm up the fresh gases and decrease the overall autoignition delay. After τ_2 , suddenly appear a very bright emission of light and a sizeable increase of pressure straightforward of the powerful exothermal autoignition. The global delay is called: $\tau = \tau_1 + \tau_2$.

After showing that the effect of temperature on the delays of autoignition (fig. 10), depends on the nature of the hydrocarbon used, and is greater for iso-butane than for n-butane, we studied the influence of equivalence ratio r .

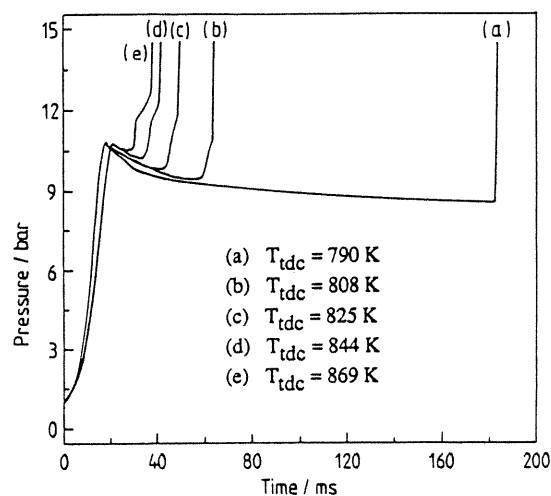


Fig. 10 Autoignition delay of n-butane.

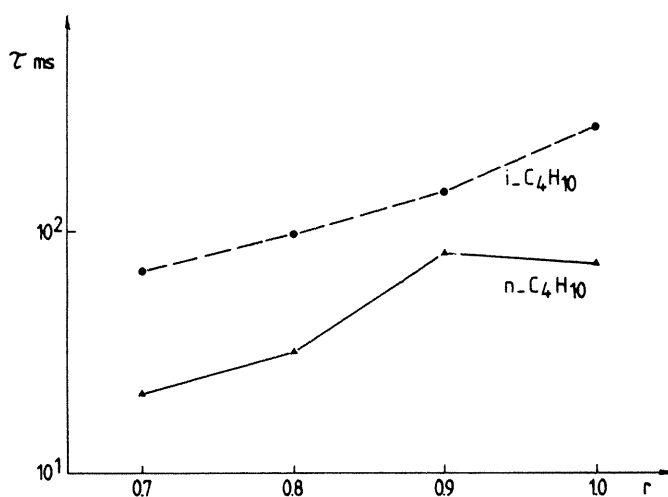


Fig. 11 Autoignition delay versus equivalence ratio.

In the experimented field ($0,7 \leq r \leq 1,0$), τ increases about linearly with r (fig. 11). Whereas the evolution of autoignition temperature T , is much more delicate to characterize in a straightforward way (fig. 12), it seems to reach a maximum value for an equivalence ratio a little smaller than the stoichiometry. This means that in an engine, where the mixture is not homogeneous, the autoignition or knocking spring out preferably where the equivalence ratio is rather weak. Perhaps it is the reason why the increasing of gas motion delayed the knocking appearance (7).

Nowadays it is always difficult to make comparisons between published data, not only because the compression durations are not the same but also for the reason that the pressures, the chamber geometry, the thermal leaks and the gas movements

are different.

For these autoignition delays, it now remains to study the influence of the pressure, to well define a test protocol and determine their values for liquid fuels.

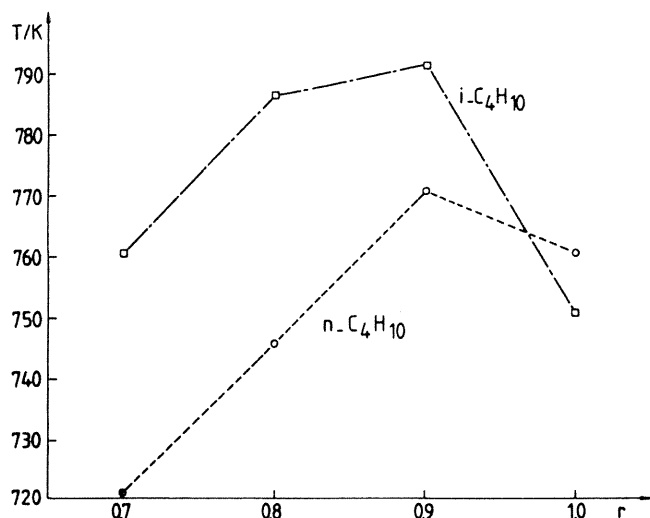


Fig. 12 Autoignition temperature.

CONCLUSIONS

A modular R.C.M. useful to study as well combustions ignited by spark, during a two stroke cycle, as autoignition, after a simple compression, was designed and built.

Using this set up and in the later way, from pressure and emitted light, the autoignition delay τ , for n-butane and iso-butane, was determined.

It is confirmed, that in the temperature range around 850 K, for these fuels, the autoignition occurs in two steps. After the first delay τ_1 , measured from the end of the compression, during τ_2 , pre-reactions warm up the mixture and lead it to autoignition.

The delay τ_2 increases with the temperature but unlike τ_1 and τ decrease.

For the iso-butane, the level of the energy

releases by pre-reactions is much lower than for the n-butane, and its delay is greater.

Under the stoichiometry, the autoignition temperature limit and the global autoignition delay decrease with the equivalence ratio.

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