Laminar-to-Turbulent Flame Transition Initiated by Generation of Instabilities in an Ignition Kernel

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A burning of combustible gaseous mixtures in an internal combustion engine (ICE) is well known to proceed mainly via a turbulent flame propagation. It is because of intensive microfluxes of reactants near a flame front that the flame propagation velocity exceeds the speed of laminar flame by several orders of magnitude. That turbulent burning is an example of a self-sustaining process characterized by a constant velocity depending, of course, on a combustion chamber geometry as well as on a fuel / air composition and initial temperature.

The corresponding coupling between chemical and gasdynamic processes is not only extremely complicated for simulation but it is hardly be affected by any external energy deposition.

Background

Attempts have been made heretofore to solve the problem of accelerated combustion in a lean-burn ICE. The methods of acceleration can be summarized as follows:

(1) Space-time optimization of the ignition. Essentially, the method is an optimization of the positions and number of spark plugs (Fuel Economy in Road Vehicles Powered by Spark Ignition Engines by J. C. Hilliard and G. S. Springer, Plenum Press, N. Y. - London, 1984).

(2) Another method is based on the use of electrical spark ignition. This method, in turn, can be subdivided as follows:

(a) A method based on the generation of power shock waves by low-induction electrical breakdown of short duration in igniters (see, e. g., 17-th Internat. Symp. on Combustion by R. Maky and M. Vogel, The Comb. Inst., p. 821, 1977).

(b) A method based on an increase of ignition energy and generation of a turbulent plasma plume in plasma-jet and surface discharge igniters of plasma (see, e. g., J. Phys. D: Appl. Phys. by P. R. Smy, *et al*., **18**, p. 827, 1985).

(c) A method based on ignition of a lean mixture by a turbulent flame of a more rich mixture in a pre-combustion chamber igniter (see, e.g., Combust. Sci. Technol. by P. L. Pitt, *et al.*, **35**, p. 277, 1984).

(3) Laser-assisted ignition that consists of replacing an electric spark with a laser spark (see, e. g., US Pat. No. 4,416,226 issued in 1983 to M. Nishida).

(4) Ignition with MW radiation (M.A.V. Ward *et al.*, US Pat. No. 4,499,872)

Analysis of the igniters described in items (1) and (2) (a), (b), (c) and their comparison in terms of energy release and volume of the ignition kernel shows that the pre-combustion chamber igniter is the most suitable one for ignition of lean mixtures. However, although the latter to some extent shortens the burning time of the combustible mixture, the effect of this shortening is insignificant and in fact does not allow the laminar stage of combustion to be shortened essentially. Plasma-jet igniters also look promising but they have an essential disadvantage, which consists of erosion of electrodes caused by high energy of ignition (~1 J).

As known from the literature (P. D. Ronney, Laser versus Conventional Ignition Flames. Optical Engineering, Feb. 1994, **33**, 510-521) and as has been found in experiments conducted by the authors (Report 86X-SP500V: Experimental Study of Laser Spark Ignition of Fuel-Air) Mixtures and Development of Theoretical Approach by E. B. Gordon, *et al*., Russian Academy of Sciences, Moscow, Russia, 1995), an ignition can be produced by picosecond-pulse laser. However, despite all advantages of laser ignition, it does not shorten a laminar stage of combustion that accounts for the most part of the charge burning.

Microwave radiation promotes ignition of lean-burn mixtures and accelerates the flame propagation (M. A. V. Ward. J. of Microwave Power, 1980, **15**, 193-202). However, the use of microwave pumping for a flame over the entire cycle of operation, as it is proposed by M. A. V. Ward *et al.* in US Pat. No. 4,499,872, needs a combustion chamber of a special configuration. This is necessary for preventing a significant shift in the cavity resonant frequency caused by reciprocating movements of the piston that constitutes one of the walls of the MW cavity. Moreover, since a Q-factor of the cavity is not so high, low concentration of electrons at a steady flame front leads to low efficiency of microwave energy absorption by these electrons. Thus, a significant part of the chemical energy released during the cycle is to be spent for generation of microwave oscillations. Nevertheless, since the MW emission can be locally absorbed by electrons, its application in combination with the conventional electron-generating discharge or laser point ignition may be promising.

As an analytical treatment shows, the noticeable effect of laser, microwave, or any other radiations on the steady-state turbulent front velocity occurs only provided an adsorbed energy becomes comparable to chemical energy of a whole charge. Moreover, as it can be shown for lean mixtures, all feasible advantages inherent to them (higher thermal efficiency and lower NO_x emission) would be lost in the case – it would be better and cheaper to use more fuel-rich mixtures.

To summarize briefly, the existing ignition systems of any type used in ICE are unable to solve the main problem, i.e., to improve performance of ICE on lean-burn mixtures without worsening other characteristics for the sake of which the transition to lean mixtures is performed.

Basic concept

In spite of low sensitivity of the flame velocity to an external influence the vortices formation, being crucial for a turbulence development, itself does not need a high input energy for its origin and maintenance.

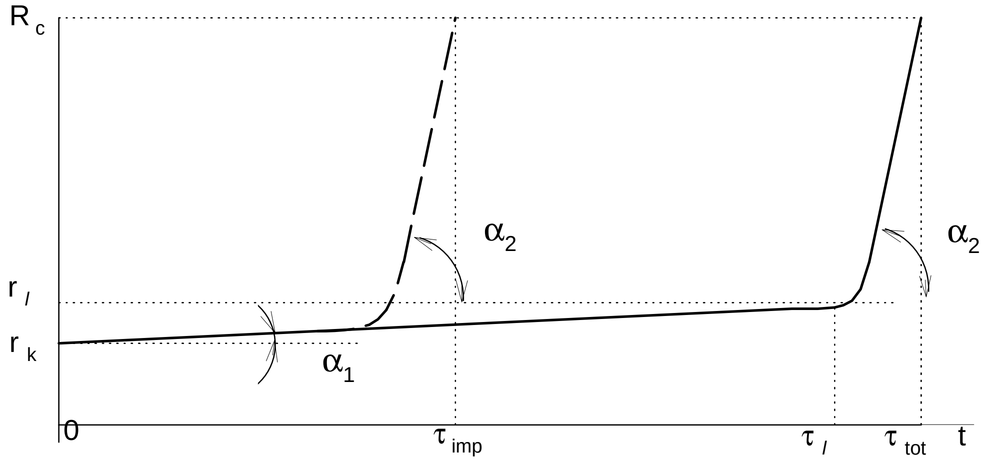

Fig. 1. Schematic temporal dependence of the flame front position inside a cylinder of ICE

In practice, under point ignition the flame always starts as laminar and thus slow flame, and only later converts to the turbulent burning. The two-stage process of combustion inside a cylinder of ICE can be more clearly understood with reference to Fig. 1 which is a graph illustrating a dependence of the flame front position on time. During the first stage, a laminar flame propagates for a short distance from initial radius $r_k \cong 1$ mm up to radius r_l equal approximately to several r_k. But this stage lasts a long time τ_l because of low velocity $V_1 = tg\alpha_1 \cong 10$ cm/s.. During the second stage, the self-sustaining turbulent combustion proceeds

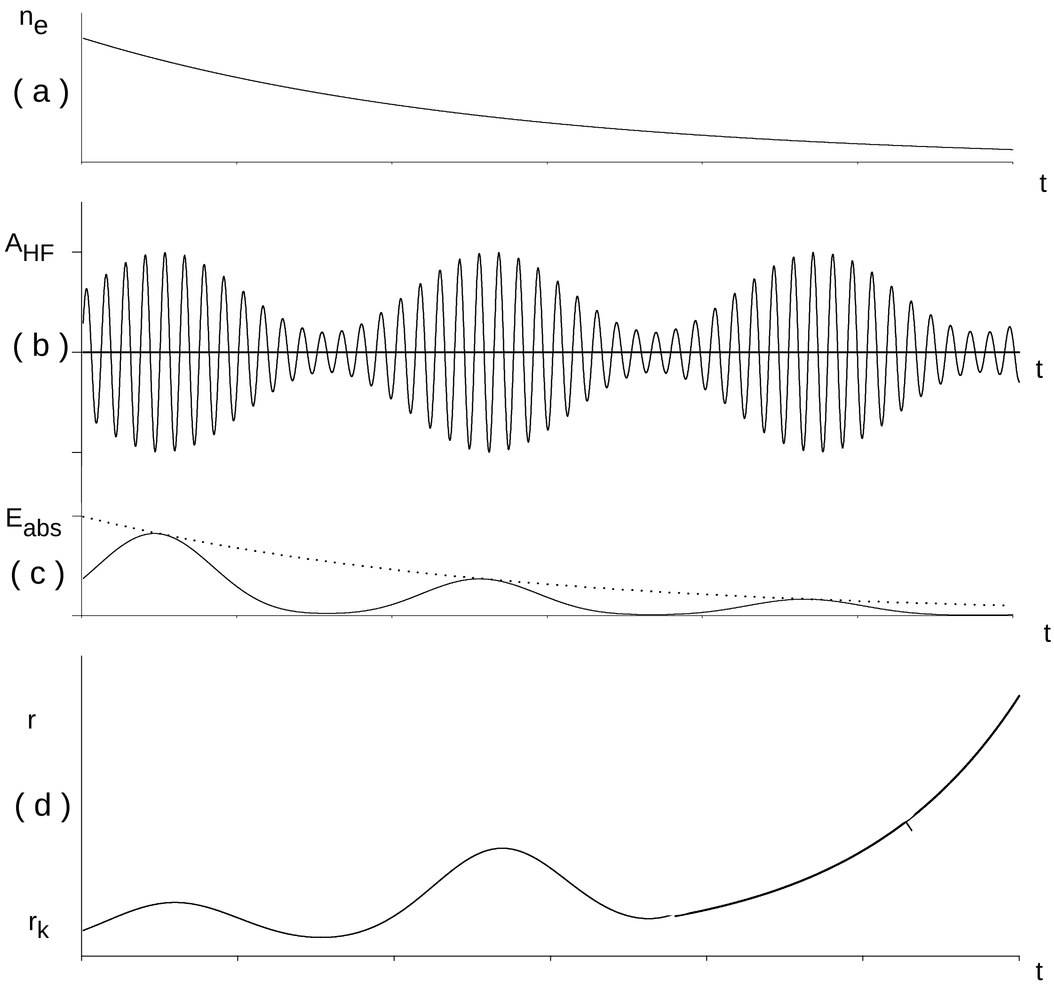

Fig. 2. The turbulence development in an ignition kernel.

with the propagation velocity $V_{pr} = tg\alpha_2 \cong 3\cdot10^3$ cm/s and the flame dimension increases up to the inner radius R_c of the combustion chamber. In spite of the fact that only 0.1% of the total

volume of a combustible mixture is burned during the first stage, the time τ_l defines in a great extent the total time of the charge burning.
A new approach to reduce the total time τ_{tot} of burning is proposed. The slow initial stage of laminar combustion is supposed to be shortened by causing externally stimulated evolution of an ignition kernel, thus leading to early transition to a turbulent flame. In Fig. 1, this is shown as a parallel shift of the start point of the second stage toward the origin of coordinates. The time difference τ_{tot} - τ_{imp} represents saving of the combustion time as a whole.
Figure 2 is a basic diagram of affecting the kernel evolution. The electric discharge or laser breakdown, being conventionally tool for a point ignition, is followed by the generation of electrons in the kernel with an electron density n_e decreasing inversely proportional in time, due to their recombination, from 10^{18} cm^{-3} at the moment of breakdown to 10^{11} cm^{-3} over the first 100 μs of the burning time (Fig. 2a). So, if one introduces a high-frequency (HF) electromagnetic (microwave or laser) field into the combustion chamber just within 50÷500μs after ignition, the energy will be absorbed only by the electrons, whereas the remaining volume of the combustion chamber will be left transparent to HF radiation. And provided HF radiation amplitude, A_{HF}, is quasiperiodically modulated (Fig. 2b) with the 10÷1000 kHz frequency (that is a range of a kernel shape instability) the ignition kernel will perceive ultrasonic oscillations at the modulation frequency, for thermal inertia of the medium smoothes the HF action. Temporal dependence of the power absorption is shown in Fig. 2c. The absorption efficiency is directly proportional to the electron concentration n_e and to the square of the HF field strength amplitude: $E_{abs} \sim n_e \times A^2_{HF}$. The thermally induced breathing pulsation of the ignition kernel deforms its shape and leads to a kernel instability up to its splitting into topological separated burned fractions which are necessary for the turbulent bulk combustion. Figure 2d shows temporal variation of the combustion zone dimension “r” from initial r_k up to final cylinder radius. In order to ensure effective splitting of the ignition kernel and to promote accelerated combustion, it is required that the modulation frequency or the frequencies combination is program-controlled to be close to that of the kernel shape instability that is defined by the type of the engine, operating conditions, and characteristics of the mixture to be combusted in the engine.
Temporal fine tuning of the amplitude modulation parameters of HF electromagnetic energy should be program-controlled to achieve the maximal output power developed by the engine. For an engine of a specific type and for specific operating conditions, as well as for the purposes of research, development and testing, an optimal parametric function required for such tuning may be determined experimentally, e.g., by means of a bench test system.
For example, the following simplest two-parametric A, α function of the amplitude modulation of HF electromagnetic energy could be used:

$$A_{HF} = A \cdot \exp (i \cdot \omega \cdot t) \ ; \qquad \omega = \omega(\alpha; t) \ ,$$

where A is the HF field strength amplitude, ω is the frequency of the kernel shape instability (since this frequency depends on the ignition kernel dimension, ω is a time-dependent function). In the first approximation which would be sufficient for reliable parametric description (see, e. g.," Hydrodynamics " by L. D. Landau, and E. M. Lifshits, Nauka, Moscow, 1988, P. 381) $\omega = \alpha \cdot (1 + (V_1 \ t / r_k))^{-1}$, where the variable α is numerically equal to the frequency of the initial kernel (having radius r_k) shape instability and V_1 is a laminar flame propagation velocity.

Initially, the tuning of the modulation function (1) to the maximum output power developed by the engine is carried out by varying the parameter α at a fixed A value, until an optimum value α_{opt} is obtained. Then at $\alpha = \alpha_{opt}$ the value of A is increased until the output power P_{out} will not essentially depend on A.

A basic diagram of the burning acceleration is covered by patent of the authors (U.S. Pat. No. 5,983,871 issued in 1999 to E.B.Gordon *et al.*). The matter of principle of the proposed model is controlling the kernel shape by modulated electromagnetic radiation with a frequency close to that of the kernel shape instability at every moment of its early evolution.

The approach is promising not only for demonstrating a possibility of the burning acceleration but also for technical application as well. It looks realistic enough to be employed in industry as far as:

- the energy consumption necessary for vortex generation constitutes a small part of energy produced by engine;
- designs of laser oscillator and MW generator are already available and their resources (especially for MW generators) exceed those of usual spark ignitor;
- a compatibility of the ICE cylinder and the input device of external energy is sure to be accessible.