Relationship between flame speed, maximum pressure and pulsation velocity in a variable volume combustion chamber

AP Shaikin, I R Galievand V E Epishkin
Togliatti State University, st.Belorusskaya, 14, Togliatti, Russia

E-mail: sbs777@yandex.ru

Abstract. The results of an experimental study of the relationship between the propagation velocity of a methane-hydrogen flame and the maximum pressure in the combustion chamber of variable volume and pulsating velocity are presented. The article shows that the influence of the pulsation velocity on the flame propagation velocity depends on the phase of combustion, i.e. the larger the size of the combustion zone, the stronger the influence of the pulsation velocity and the coefficient of excess fuel. When stoichiometric mixtures are burned, an increase in the pulsation velocity leads to a more noticeable increase in the flame velocity than when burning poor and rich mixtures. It was experimentally found that, despite the change in the coefficient of excess air, the concentration of hydrogen in the fuel and the pulsating velocity, a direct linear dependence of the maximum pressure in the combustion chamber on the flame propagation rate is maintained. Processing the results of foreign scientists showed the validity of the laws we obtained for combustion chambers of various designs. The results of the work can be used in the design and development of energy-efficient and low-emission combustion chambers of variable volume.

1. Introduction
In connection with the increasing environmental and economic requirements for power plants, issues of their further improvement become relevant. Over the past two decades, scientists and engineers from leading countries of the world (USA, England, China) have been paying great attention to the new fuel hythane - a mixture of methane and hydrogen [1]. The interest of industry and science in hythane is due to the following circumstances: 1) the use of hythane contributes to a significant reduction in the toxicity of exhaust from a power plant and an increase in its traction and dynamic characteristics; 2) it is possible to use existing gas filling compressor stations and gas equipment; 3) the cost of hythane does not exceed the cost of gasoline. To create new low-emission and energy-efficient combustion chambers (CC) using hythane, an in-depth study of the combustion process of composite fuel is necessary. At present, the influence of the pulsation velocity on the propagation velocity of a methane-hydrogen flame under conditions of a variable CC volume remains little studied. There is no data on the relationship of the flame velocity with the maximum pressure in the CC. The results of the study will reduce time and money when creating new power plants using hythane that meet modern requirements for power, efficiency and toxicity of exhaust gases.

The aim of this work is to study the relationship of the propagation velocity of a methane-hydrogen flame with a pulsating velocity and maximum pressure in a variable volume combustion chamber.
2. Research methodology

The experiments were carried out in a CC of variable volume with spark ignition. Hythane was used as fuel. The pulsation speed was changed by changing the rotational speed of the crankshaft of the piston power plant ($n$) from 600 to 900 min$^{-1}$. Variable factors in the experiments were the excess air coefficient ($\alpha$) and the hydrogen concentration in hythane, $r=29, 47, \text{ and } 58\%$ (by volume). The experimental technique consisted of parallel registration of signals from an ignition spark, an air flow sensor, and a pressure sensor. The flame propagation rate was determined using ionization sensors, one of which was located near the spark plug, and the other in the remote zone of the CC [2]. The flame propagation velocity was studied in the first and second (main) phases of combustion. The first phase of combustion corresponds to the propagation of the flame near the spark plug, in which the formation of the front of the turbulent flame takes place. The flame propagation velocity in the first phase depends on the normal flame velocity, the magnitude of small-scale turbulence, as well as the physicochemical properties of the fuel-air mixture (FAM). In the second (main) phase of combustion, combustion of the bulk of the fuel assembly is observed due to the development of a turbulent flame front to a larger volume of CC.

3. Research results

As a result of the analysis of experimental data, it was found that an increase in the pulsation velocity by a factor of 1.5 leads to an increase in the flame velocity only in the second phase of combustion, while a change in the concentration of hydrogen in FAM practically does not affect this regularity (figure 1). This is explained by the fact that at the first phase of combustion, the flame is a small burning area and it is more difficult for turbulent vortices to affect the shape of the flame than when the flame increased in size. Since, the smaller the burning zone, the greater the hydrodynamic resistance to external influences. This tendency is especially pronounced during FAM combustion with a coefficient of excess air from 0.9 to 1.1. The regularity shown in figure 1 is explained by the fact that for air excess coefficients from 0.9 to 1.1, combustion in the CC is described by the micro-laminar flame model, i.e. the Karlovitz number is less than one, and the Damkeler number is more than one. Turbulent vortices do not penetrate into the zone of chemical reactions of the flame, but only change its configuration, therefore, an increase in the pulsation velocity leads to an increase in the surface area of the flame front and, as a consequence, to an increase in the flame propagation velocity.

![Figure 1. Change of the flame propagation velocity in the second phase of combustion with an increase in pulsation velocity by 1.5 times.](image_url)

Also figure 1 shows that when burning poor mixtures, an increase in the flame velocity due to an increase in the pulsation velocity decreases. This is due to the fact that when lean mixtures are burned ($\alpha > 1.1$), the width of the laminar flame increases, turbulent eddies penetrate the zone of chemical reactions of the flame and affect the kinetics of chemical reactions, i.e. Karlovits and Damkeler numbers are greater than one. Turbulence of the flow leads to rupture of the zone of chemical reactions and a decrease in the speed of flame propagation. Note that similar results were obtained
when analyzing the data of Dutch scientists [3], who studied the influence of the rotational speed of the crankshaft of a piston power plant on the speed of flame propagation in a CC of variable volume. And also [4] experimentally shows the influence of the pulsation velocity on the flame propagation velocity at different moments of fuel combustion in a constant volume CC.

Thus, it was found that the influence of the pulsation velocity on the flame propagation velocity depends on the phase of combustion (the larger the size of the combustion zone, the stronger the influence of turbulence), the coefficient of excess fuel (for $\alpha$ from 0.9 to 1.1, an increase in turbulence leads to a more noticeable an increase in flame velocity than for $\alpha > 1.1$ and $\alpha < 0.9$) and does not depend on the concentration of hydrogen in the fuel. Processing of experimental data obtained by other scientists has shown that the patterns we have revealed are applicable to CC of different designs using different hydrocarbon fuels. The study of the behavior of the flame velocity with a change in the ratio of methane and hydrogen fractions showed that the higher the concentration of hydrogen in methanol, the higher the flame propagation velocity in both phases of combustion. It is noted that a similar behavior of the flame velocity was recorded when processing experimental data from other scientists. In a joint work of scientists from the Texas A&M University and the Irish National University [5], a decrease (relative to stoichiometry) of the turbulent and laminar flame velocity during the combustion of rich mixtures of methane with hydrogen was recorded. Dutch scientists from the technical University of Eindhoven, who studied the turbulent speed of a methane-air flame in a single-cylinder engine with spark ignition, revealed an increase in the speed of flame propagation in the main phase of combustion when stoichiometric fuel mixtures are burned and when the crankshaft rotates from 600 to 1350 min$^{-1}$ [3]. Similar results were obtained when analyzing the work of Indian scientists from the Gandinagar Technical University [6], who conducted research on a gas piston engine, as well as Belgian scientists from the University of Ghent [7].

An analysis of experimental data revealed that the promoting effect of hydrogen on flame velocity is more pronounced in the first phase of combustion. This is due to the fact that in the second phase of combustion, the flame propagation process is determined mainly by factors of large-scale turbulence, in contrast to the first phase, in which the combustion process strongly depends on the physicochemical properties of fuel assemblies. It is also worth noting that similar results were obtained when processing experimental data presented in [8], which was devoted to studying the effect of 15% hydrogen addition on the combustion process in a gas piston engine. An analysis of the work of American scientists [5] recorded an increase in the turbulent and laminar flame velocities when burning mixtures of methane with hydrogen in amounts of 50, 70 and 90%, while the higher the concentration of hydrogen and the coefficient of excess air, the more the flame increased. Similar results were obtained when processing studies conducted by Turkish [9] and Italian scientists [10].

Figure 2 shows the dependence of the maximum pressure in the CC of variable volume on the propagation velocity of a methane-hydrogen flame with a change in the pulsation velocity, coefficient of excess air, and hydrogen concentration.

![Figure 2](image-url)
It has been experimentally revealed that an increase in the flame propagation velocity contributes to an increase in the maximum pressure in a pressure medium of variable volume. It is noted that this trend persists with a change in the pulsation velocity, the coefficient of excess air and the concentration of hydrogen in hydrocarbon fuel. The result obtained is in good agreement with experimental data on the effect of the rate of fuel combustion on the pressure in the CC of a piston engine; in particular, an analysis of [11] showed that the higher the rate of combustion, the higher the pressure and its growth rate in the CC. This fact is explained by the fact that the higher the speed of flame propagation, the faster and with greater heat release the fuel burns in a smaller volume of CC and, therefore, higher pressure.

4. Conclusion
The influence of the pulsation velocity on the flame propagation velocity depends on the phase of combustion (the larger the size of the combustion zone, the stronger the influence of the pulsation velocity), the excess fuel coefficient (for $\alpha$ from 0.9 to 1.1, an increase in the pulsation velocity leads to a more noticeable increase in the velocity flame, rather than at $\alpha>1.1$ and $\alpha<0.9$) and does not depend on the concentration of hydrogen in the fuel.

It has been experimentally revealed that an increase in the speed of flame propagation contributes to an increase in the maximum pressure in a CC of variable volume. It is noted that this trend persists when the pulsation velocity, the coefficient of excess air and the concentration of hydrogen in the fuel change.

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