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Study of combustion process with jet-ignition of propane-air mixtures

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Abstract. The paper presents the study of combustion process of a homogenous lean propane-air mixture in the cylindrical combustion chamber ignited by a hot gas jet from the pre-ignition chamber. A rich propane-air mixture in the pre-chamber is ignited by the spark plug and the exhaust gasses flow from the chamber trough the holes in the wall. The mathematical model of gas exchange and energy balance in chambers with a laminar finite-rate model taking into account the two-step Arrhenius chemical kinetics is presented. The work presents results of thermodynamic parameters of the charge obtained in CFD simulations in Fluent and Kiva3v for three configurations: with one hole in the wall of the ignition chamber, with three holes and without an ignition chamber. Modelling and simulation have shown faster burning of the mixture for jet ignition with three holes of the pre-chamber. The results of simulations were verified by experimental studies in the combustion chamber of the same geometry by the Schlieren method. The work presents flame front propagation, pressure traces and pressure increment speed for two mixtures with a different equivalence fuel-air ratio. Experimental results proved the simulation observation of faster flame propagation in the main chamber with three holes.

Key words: gaseous mixture, combustion, jet ignition.

1. Introduction

The study was of a combustion system where the flame was initiated by a jet, or, jets flowing through the orifices in a pre-ignition chamber, this domain has been reported by Gussak [1, 2], Karpov [3, 4], Zeldovich [5, 6] and Oppenheim [7–10]. Here, results comparing combustion pressures for combustion initiated by means of a jet ignition system, the pre-ignition chamber, and a conventional ignition system are given. The paper also explains the benefits of lean mixtures in relation to combustion pressure for mixtures of different equivalence ratio. New results were obtained for the flame velocity. Especially the volumetric flame velocity in cases where the pre-ignition chamber was used with one and three jets penetrated into the main combustion chamber. The results were interesting in that the flame propagation was almost as a plane front. These compare with other results for pressures and their derivatives given in [11, 12].

The combustion process in the combustion chamber of reciprocating engines takes place at a high air flow caused by an inflow effect through the valves or inlet ports. The high turbulence of the charge causes better fuel mixing with the air and influences on higher speed of the flame propagation from the spark plug. The burning of the mixture occurs in transient conditions at changeable volume, pressure, temperature, mole fraction of species. This affects the variability of thermodynamic parameters such as: specific heat ratio κ, diffusivity D, viscosity μ, heat transfer and also on fuel evaporation. A combustion process in IC engines is depended mostly on turbulent burning speed which is about ten times higher than laminar burning speed. In order to find new combustion systems the research works are often conducted in the combustion chamber with a constant volume. In that case the fuels with the high octane number (ON) are applied and the burning is initiated by ignition of the spark plug. The mixture is usually premixed with a constant air-fuel ratio. In the first period the flame front moves with laminar speed by diffusion. In such conditions the flame propagation is very slow. The increasing movement of the flame causes strong turbulence of the charge near the flame. The experiments in the combustion chamber enable the observation of the flame movement, pressure measurement and turbulence flow. Previously, many experiments have been done on the test benches by researchers in the world for observation of a combustion process of different fuel mixtures. Oppenheim [11] proposed the combustion of homogeneous lean mixture by the rich fuel mixture jet ignited by the spark plug. Polish researchers Kowalewicz [13] and Stelmasiak [14] have tested the combustion process of CNG homogeneous mixture at stoichiometric composition ignited by the jet of diesel oil at different engine speeds and loads. Zhukov *et al.* [15] have done the experimental work on the special bench for combustion of kerosene mixture by fuel jest in the jet engines in airplanes. The data obtained at the Department of Aerophysics and Space Research in Moscow allows for validating kinetic models of the burning of kerosene, which is a complex mixture of various hydrocarbons. The other way of ignition of air-fuel mixture by a high speed plasma jet was investigated by Afanasiew *et al.* [16]. They studied the conditions of ignition and the velocities of propagation of flame in a premixed methane-air charge in a semiclosed tube upon ignition at the closed end of the tube with a point

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spark and a high-speed pulsed plasma jet flowing out of a pulsed plasma accelerator. The aim of the proposed work was to investigate by experiment and modelling the combustion process of a lean propane-air mixture by electrically ignited the rich mixture jet of the same fuel.

2. Mathematical model of combustion and flow

2.1. Burning of propane-air mixture. Combustion of the propane-air mixture can be modelled by single step reaction or two step reaction where decay CO_2 on CO and O_2 is also considered. The authors took into account two-step reactions because in real conditions there are dissociation reactions as a result of high temperature of combustion process. The chemical reactions with Arrhenius parameters of two-step model are presented in Table 1. The gas fuel was chosen for the case of better diffusion such fuel with air and homogeneous mixture forms very fast.

Table 1
Propane-air two-step chemical reactions with Arrhenius coefficients

Reaction No	Reaction	Pre-exponential factor A_i [kmol/(m^3·s)]	Activation energy E_i [J/kmol]
1	C_3H_8 + 3.5 O_2 = 3CO + 4H_2O	5.62 e+09	1.256 e+08
2	CO + 0.5 O_2 = CO_2	2.239 e+12	1.7 e+08
3	CO_2 = CO + 0.5 O_2	5.0 e+08	1.7 e+08

2.2. General spatial modelling of the combustion process in the combustion chamber. The simulation model of the mixture burning in the experimental combustion chamber takes into account all boundary and initial conditions. The cylindrical combustion chamber with volume V shown in Fig. 1 was filled with the lean air-propane mixture. Small additional semi-spherical chamber separated from the main chamber was located in the symmetry cross section of the combustion chamber near the wall and was connected to the main chamber trough the small cylindrical channels with diameter d. This small chamber had volume V_i and was filled by rich air-fuel mixture.

2.3. Species transport in chemical reactions. The considered gas flow and combustion process of the propane-air mixture in the tested combustion chamber can be treated as single-phase flow, where both the air and propane are in gaseous state. The change of local mass fraction of each chemical species was calculated from the general form of transport conservation equation:

$$\frac{\partial}{\partial t}(\rho c_i) + \nabla \cdot (\rho \mathbf{u} c_i) = -\nabla \cdot \overline{G}_i + R_i + S_i, \qquad (1)$$

where c_i – local mass fraction of species i, ρ – density of the gaseous phase, $\mathbf{u}$ – gas velocity vector, $\overline{G}_i$ – mass diffusion in turbulent flow, R_i – net rate of production of species i, S_i – rate of additional source from the disperse phase.

At assumption of turbulent flow the mass diffusion takes into account also the mass diffusion of laminar flow and can be written as:

$$\overline{G}_i = -\left(\rho D_{m,i} + \frac{\mu_t}{Sc_t}\right)\nabla C_i - D_{T,i}\frac{\nabla T}{T}, \qquad (2)$$

where $Sc_t = \dfrac{\mu_t}{\rho D_t}$ – turbulent Schmidt number (μ_t – turbulent viscosity, D_t – turbulent diffusivity), $D_{m,i}$ – mass diffusion coefficient for species i in the mixture [m^2/s], $D_{T,i}$ – Soret thermal diffusion coefficient, T – temperature.

In the simulation the turbulent Schmidt number was calculated but normally it equals to 0.7.

When turbulent flow is neglected ($\mu_t = 0$) then Eq. (2) has a simple form without the term $\dfrac{\mu_t}{Sc_t}$.

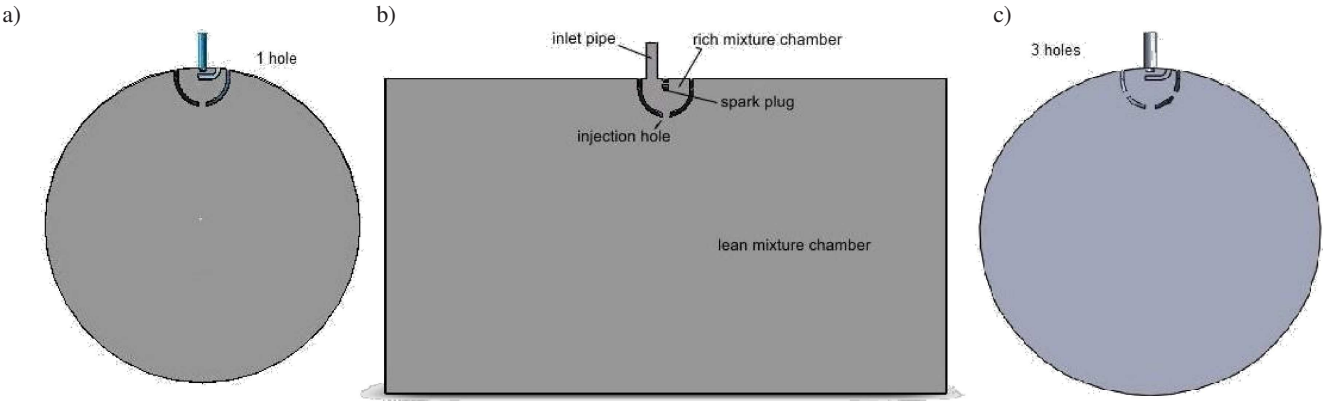


Fig. 1. Cross sections of combustion chamber with two volumes: a) pre-chamber with one jet-hole, b) axial cross section of the combustion vessel, c) pre-chamber with three jet-hole

The diffusion coefficients D of two gaseous species A and B are a certain function of a molar volume of species V_A and V_B, molecular weight M_A and M_B, pressure p and temperature T given below by EPA[1] [17]:

$$D = 0.001\ T^{1.75} M_r^{0.5} / \left(p \left(V_A^{1/3} + V_B^{1/3} \right)^2 \right)\ [\mathrm{cm}^2/\mathrm{s}], \tag{3}$$

where $M_r = (M_A + M_B)/(M_A M_B)$, V in cm^3/mol, M in g/mol T in K and p in bar. At two-equations standard turbulent flow model $k-\varepsilon$ the turbulent viscosity μ_t was calculated as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

whereas $C_\mu = 0.09$ was assumed as constant. The another turbulent coefficients have assumed the constant values $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$.

This model was implemented in a computer program for calculation of the diffusion coefficient of chemical species in the air as a main gas. Initially in the combustion chamber the propane-air mixture is in steady state conditions and for such a reason the chemical reaction rates were calculated for laminar flow by using the laminar finite-rate model with two-step Arrhenius chemical kinetics.

The chemical reactions of species i for reaction r in the system are usually presented in the form:

$$\sum_i a_{i,r} x_i \leftrightarrow \sum_i b_{i,r} x_i, \tag{5}$$

where x_i represents one mole of species i and $a_{i,r}$ and $b_{i,r}$ are integral stoichiometric coefficients for reaction r.

This has not increased so much in the computation time but gives a view of the flame propagation. In calculations the backward reactions were neglected and the molar rate of creation or destruction of chemical species i in reaction r in (1) is given by:

$$\dot{R}_{i,r} = \Gamma \left(b_{i,r} - a_{i,r} \right) \left(k_{f,r} \prod_{j=1}^{N} \left[C_{j,r} \right]^{\left(n'_{j,r} + n_{j,r}" \right)} \right), \tag{6}$$

where $C_{j,r}$ – molar concentration of species i in reaction r [kmol/m^3], $n'_{j,r}$ – rate exponent for reactant species j in reaction r, $n_{j,r}$" – rate exponent for product species j in reaction r $k_{f,r}$ – Arrhenius forward rate constant for reaction r.

The Γ represents the net effect of third bodies but the reactions have not include it and for the case $\Gamma = 1.0$. The net source of each chemical species with molecular weight $M_{w,i}$ was calculated from all N reactions as follows:

$$R_i = M_{w,i} \sum_{r=1}^{N} \dot{R}_{i,r}. \tag{7}$$

The exponent coefficients in considered chemical reactions are shown in Table 2.

Table 2
Exponent coefficients in chemical reactions for 2-step propane-air mixture combustion

Reaction No	Rate exponent for reactant No 1	Rate exponent for reactant No 2
1	0.1	1.65
2	1	0.25
3	1	

The heat released during combustion process is the additional source $\dot{Q}_c$in the equation of internal energy balance:

$$\dot{Q}_c = \sum_{r=1}^{N} Q_r \dot{R}_r, \tag{8}$$

where Q_r is the negative of the heat of reaction at absolute zero and is determined from:

$$Q_r = \sum_i \left(a_{i,r} - b_{i,r} \right) \left(\Delta h_f^0 \right)_i, \tag{9}$$

where $(\Delta h_f^0)_i$ is the heat formation of species i at absolute zero.

2.4. Spark ignition model. The transport of chemical species in the combustion chamber involved by the spark plug for the mean reaction progress variable c can be defined according to the general formula [18]:

$$\frac{\partial(\rho_c)}{\partial t} + \nabla \cdot (\rho \mathbf{v} c) = \nabla \cdot (D_t \nabla c) + \rho_u U_t \left| \nabla c \right|, \tag{10}$$

where D_t – turbulent diffusivity, ρ_u – density of unburned mixture, U_t – turbulent flame speed determined from Zimont closure model, ρ – mean mixture density, c – mass ratio of species in the mixture, $\mathbf{v}$ – velocity vector.

In the first period, when the spark kernel is very small compared to the mesh size the transport Eq. (1) was adopted to the laminar flow and was written in the following form:

$$\frac{\partial(\rho c)}{\partial t} + \nabla \cdot (\rho \mathbf{v} c) = \nabla \cdot ((\kappa + D_{tt}) \nabla c) + \rho_u U_t \left| \nabla c \right| \tag{11}$$

where κ – laminar thermal diffusivity ($= k/(\rho c_p)$ wherein k – thermal conductivity and c_p is a specific heat at constant pressure.

The effective diffusivity D_{tt} is given by:

$$D_{tt} = \begin{cases} D_t \left(1 - \exp\left(\dfrac{-t_{td}}{\tau'} \right) \right) & \text{if } t_{td} \geq 0 \\ D_t & \text{if } t_{td} < 0 \end{cases} \tag{12}$$

where $t_{td} = t - t_{ig}$ denotes the time of spark initiation since ignition time t_{ig} and τ' is an effective diffusion time given by user usually about 0.00001 s. The turbulent scales that are smaller than the spark radius may contribute to turbulent spark diffusion. Effective diffusivity grows with the time and this creates higher temperature around the electrodes of the spark plug, which can cause convergence difficulties. The sparking is caused by the energy supplied to the spark plug

[1] United States Environmental Protection Agency

by the electrical system. Generally the energy delivered to the spark plug by the ignition system is 50–100 mJ during 1–1.5 ms.

3. Simulation of propane-air mixture combustion

Simulation of combustion process of lean propane-air mixture ignited by the rich mixture jet with high temperature was carried out by using of 3D computational model in Ansys-Fluent CFD programme [18]. Modelling of gas flow besides of mass, momentum and energy balance equations [4] and chemical reactions takes into account also turbulence [7]. Geometry of the calculation model was the same as the real tested chamber with short inlet duct with rich mixture. The cylindrical chamber ($d = 83$ mm, $L = 122$ mm) with two separated volumes was replaced by 88525 tetrahedral cells and only 146 hexahedral cells and 173211 triangular interior faces. The following initial conditions were assumed:

- initial pressure 0.1013 MPa,
- initial temperature 350 K,
- wall temperature 300 K,
- constant spark diameter 1.5 mm,
- ignition time 0.001 s,
- ignition energy 0.1 J,
- propane mass fraction in main chamber 0.06,
- oxygen mass fraction in main chamber 0.219,
- propane mass fraction in rich mixture chamber 0.09,
- oxygen mass fraction in rich mixture chamber 0.21,
- diameter of the main injection hole diameter 2.5 mm.

The cross section of the computational model is shown in Fig. 1. The pre-chamber was separated from the combustion chamber by a thin half-spherical steel wall with one or three holes connected two volumes.

Mixture equivalence ratio in the main chamber amounted 0.75 and 1.7 in the pre-chamber. Additionally, a comparison of combustion parameters in a simulation process was done for the cylindrical chamber with the same geometry but without a small ignition chamber for mixtures with stoichiometric composition ($\phi = 1.0$) and lean mixture ($\phi = 0.75$). Simulations of a combustion process in the combustion chamber with two chambers were carried out using CFD technique in Ansys-Fluent v.13.0 in the Windows system and for a fully cylindrical chamber in Kiva3v.

4. Calculation results of simulation

After ignition the speed of the combustion process in the rich mixture chamber is very slow, as a result of absence of charge turbulence. The thermal energy delivered by the spark plug initially heats the charge from initial temperature $T = 350$ K to the ignition temperature of the rich propane-air mixture about 740 K. Initiation of chemical reactions occurs after 4 ms from ignition start. Very slow flame propagation in the pre-chamber causes also very low velocity of the mixture jet flowing into the main combustion chamber. Contours of net mass reaction rate of propane [kg/(m^3 s)] at different time (0.01, 0.02 and 0.026 s) is presented in Fig. 2. The equivalence ratio of the mixture ϕ in the pre-chamber amounted

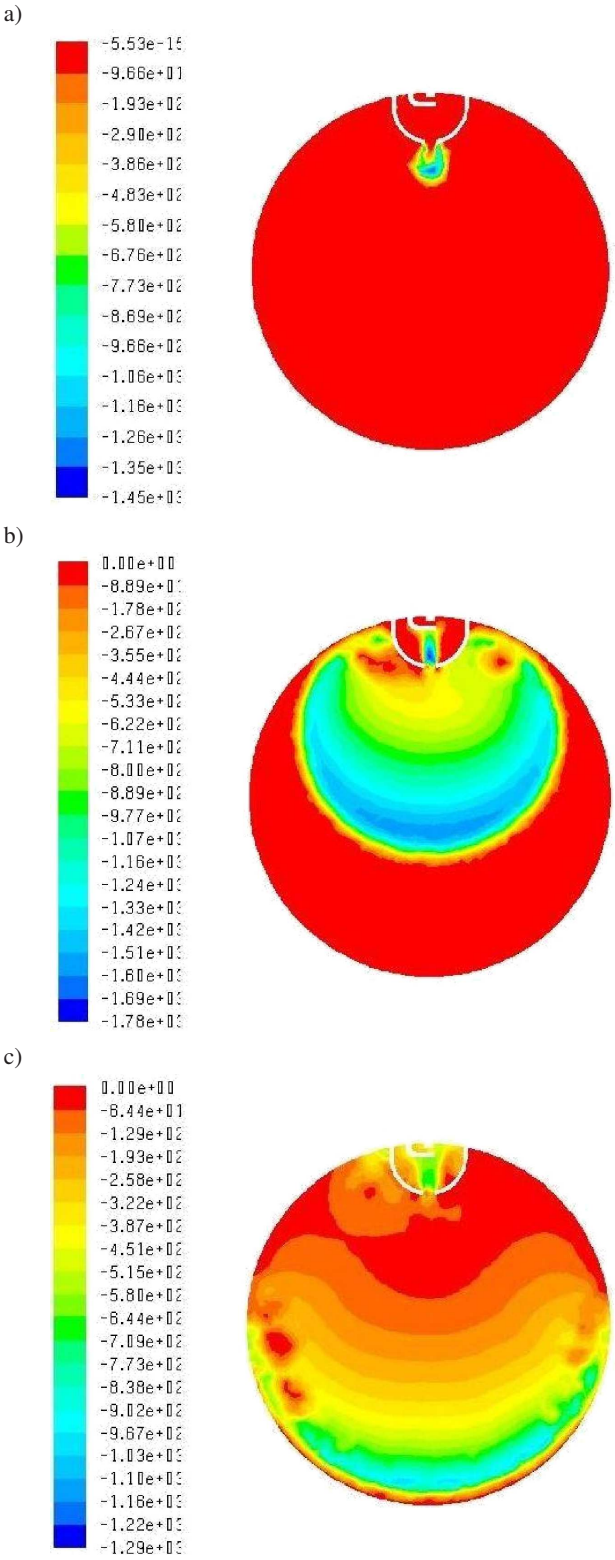


Fig. 2. Contours of net reactions rate of C_3H_8 [kg/(m^3 s)] at time: a) 0.01, b) 0.02 and c) 0.026 s after start of ignition with one outflow hole of rich mixture chamber

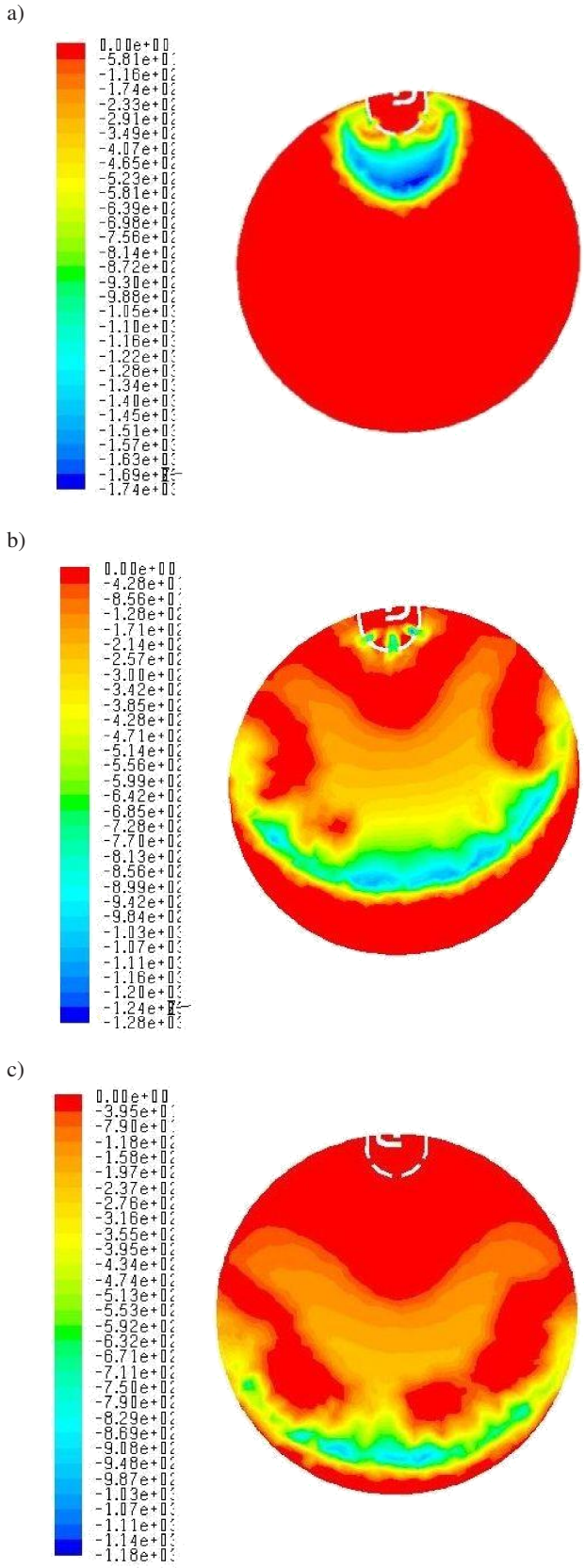


Fig. 3. Contours of net reactions rate of C_3H_8 [kg/(m^3 s)] at time: a) 0.01, b) 0.02 and c) 0.026 s after start of ignition with three outflow holes of rich mixture chamber

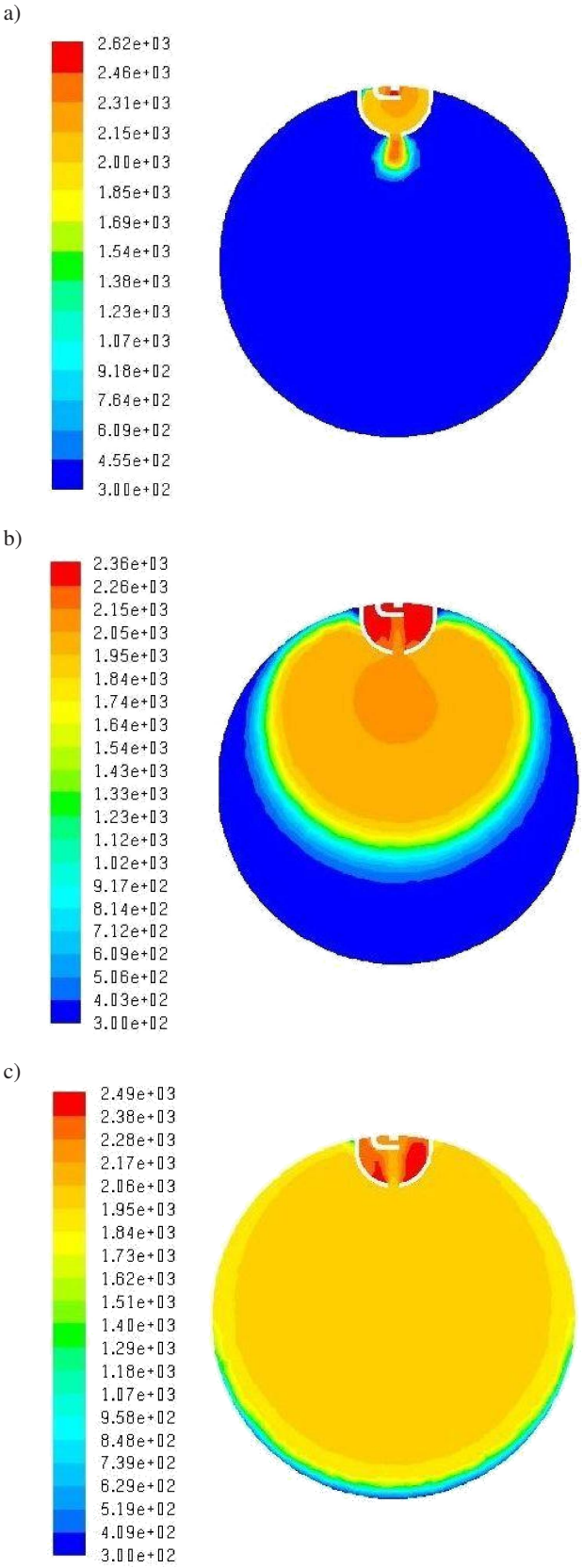
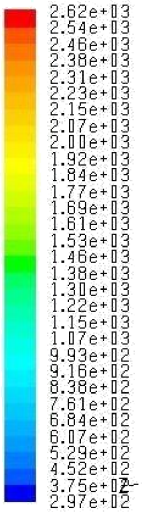
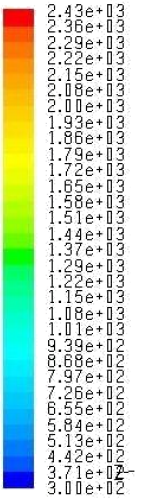


Fig. 4. Contours of temperature [K] at time: a) 0.01, b) 0.02 and c) 0.026 s after start of ignition with one outflow hole of ignition chamber

a)



b)



c)

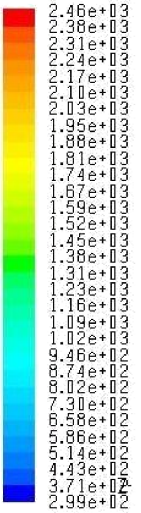


Fig. 5. Contours of temperature [K] at time: a) 0.01, b) 0.02 and c) 0.026 s after start of ignition with three outflow holes of ignition chamber

to 1.7 and in the main chamber 0.75. Only one outflow hole causes a spherical propagation of the flame and all the time chemical reactions occur in the small chamber. The combustion effect is recognized by lower values of reaction rate (blue colour). Applying of three holes influences on extension of the flame front and causes higher combustion speed in the main chamber. The effect of the flame propagation as a result of reaction rate of propane-air mixture at three holes is shown in Fig. 3. In a final step the flame has also spherical shape with a great side impact of two additional holes. Velocity of propagation of the flame in this case is higher than for previous case with one hole. The simulated combustion speed in the main chamber with only one hole amounts about 4.25 m/s and with three holes amounts 5.9 m/s and is about 30% higher. The distribution of temperature in the combustion chamber depends on the equivalence ratio of the mixture and is higher in the small chamber than in the main chamber. It grows with the flame propagation. Contours of temperature in the cylindrical combustion chamber with one outflow hole at different time steps are presented in Fig. 4. Maximum of temperature in the ignition chamber amounts to 2600 K and mean temperature of burned mixture is almost constant and is lower than 2000 K. The faster combustion process in the combustion chamber with three holes does not influence on a temperature value (Fig. 5). The mean temperature of burned mixture does not exceed 2000 K and is almost constant because of a homogenous mixture.

The ignition chamber with only one hole gives later burning of the air-fuel mixture. The number of the jet holes influences also on an increment of pressure, which is shown in Fig. 6. The earlier increase of pressure occurs for the chamber with three holes. However, maximum of pressure for both cases has the same value 0.65 MPa. Courses of pressure are a function of burning of amount of fuel. The mean propane mass fraction is presented in Fig. 7 in terms of time. The graph show total mass of propane burning in whole cylinder with

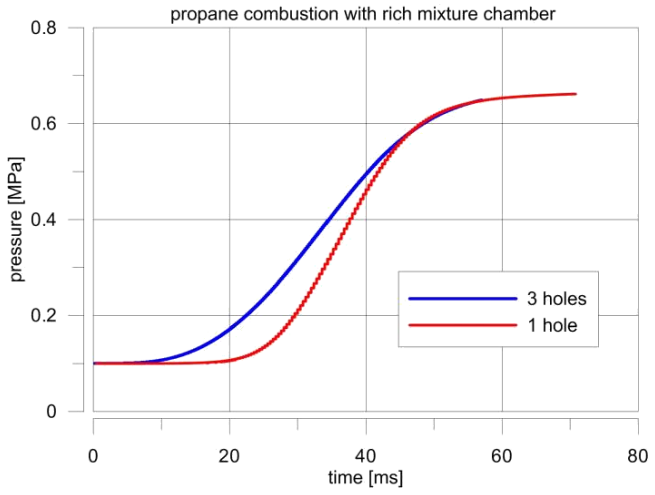


Fig. 6. Comparison of pressure trace during combustion process in the combustion chamber with 1 and 3 outflow holes from rich mixture chamber

volume 757 cm^3. In real SI engine the combustion chamber does not exceed 60 cm^3 during combustion process. Applying three holes contributes to the faster burning speed of mixture in a real SI engine. The combustion process in the cylindrical chamber with big volume contributes also in lower mean temperature of the charge not higher than 2000 K (Fig. 8). The combustion process runs in conditions of laminar flow of premixed charge.

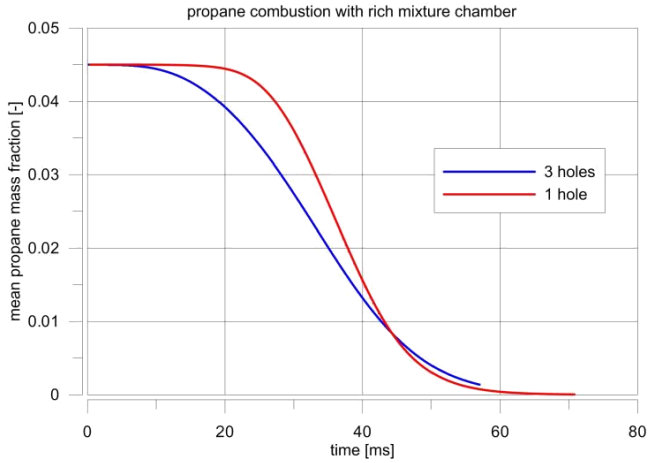


Fig. 7. Comparison of mean propane mass fraction during combustion process in the combustion chamber with 1 and 3 outflow holes from rich mixture chamber

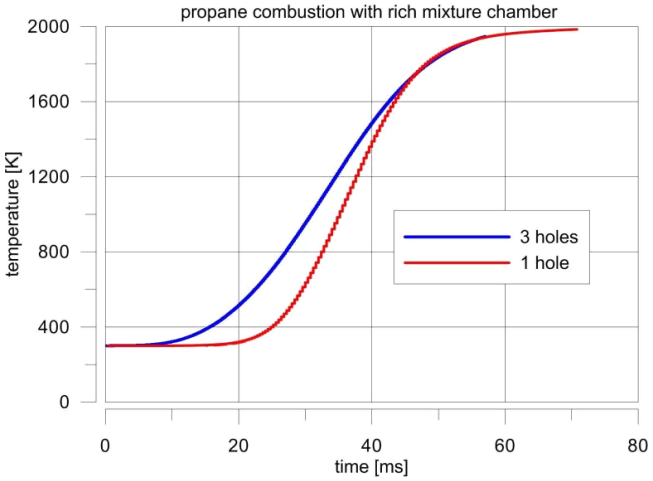


Fig. 8. Comparison of mean temperature during combustion process in the combustion chamber with 1 and 3 outflow holes from rich mixture chamber

5. Combustion process in one cylindrical chamber

The burning process of a propane-air mixture in a normal cylindrical chamber without the ignition chamber but with the same dimensions as previous cases was considered additionally. Ignition of the mixture occurs also in the middle cross section of the cylinder with the same ignition parameters. On the basis of simulation results very fast burning of fuel in the chamber filled with stoichiometric mixture with $\phi = 1.0$ (Fig. 9) was found. For leaner mixture ($\phi = 0.75$) the combustion process is about 60% slower.

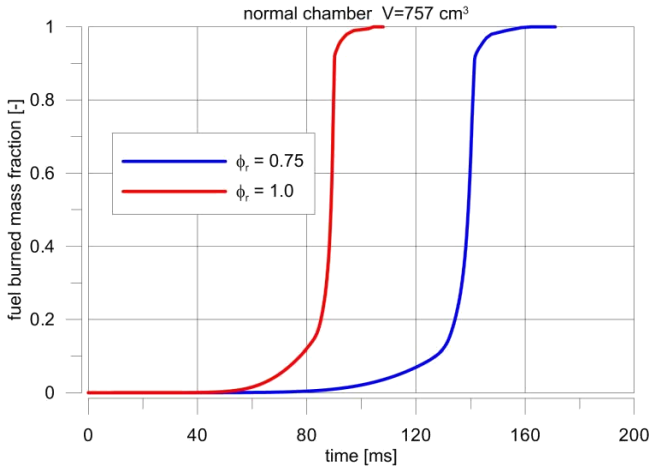


Fig. 9. Burned mass fraction of fuel in normal chamber filled with propane mixture with two equivalence ratios 0.75 and 1.0 (initial pressure 0.1 MPa and initial temperature 350 K)

This is seen also on pressure traces of both combustion processes (Fig. 10) and also on stoichiometric mixture maximum pressure which is higher than for a lean mixture but does not exceed 0.8 MPa. The real combustion process in the chamber begins after 30 ms from the beginning of ignition. The progress of the combustion process represented by temperature for two propane-air mixtures with the lean and stoichiometric composition at the same time is presented in Fig. 11 (60 ms after ignition). The spherical flame front moves almost two times faster for $\phi = 1.0$ than for mixture with $\phi = 0.75$. The temperature of the burned mixture amounts to 2300 K for stoichiometric mixture and is higher than for the case with the additional ignition chamber (a temperature lower than 2000 K). The similar problem of combustion jet ignition was considered in the following papers [19–21].

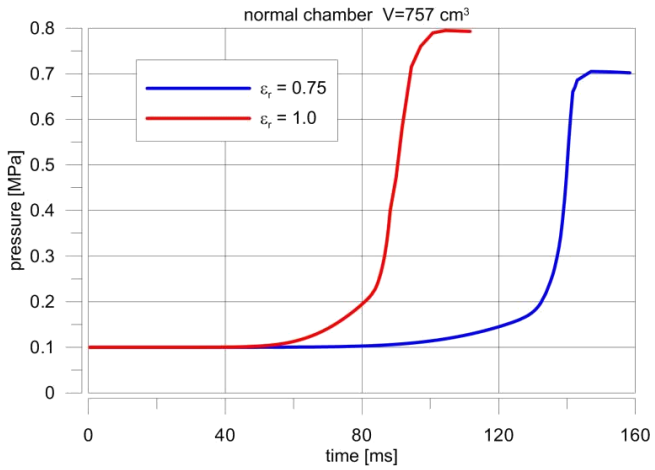


Fig. 10. Comparison of pressure in normal chamber during combustion of propane mixture with two equivalence ratios 0.75 and 1.0 (initial pressure 0.1 MPa and initial temperature 350 K)

a)

b)

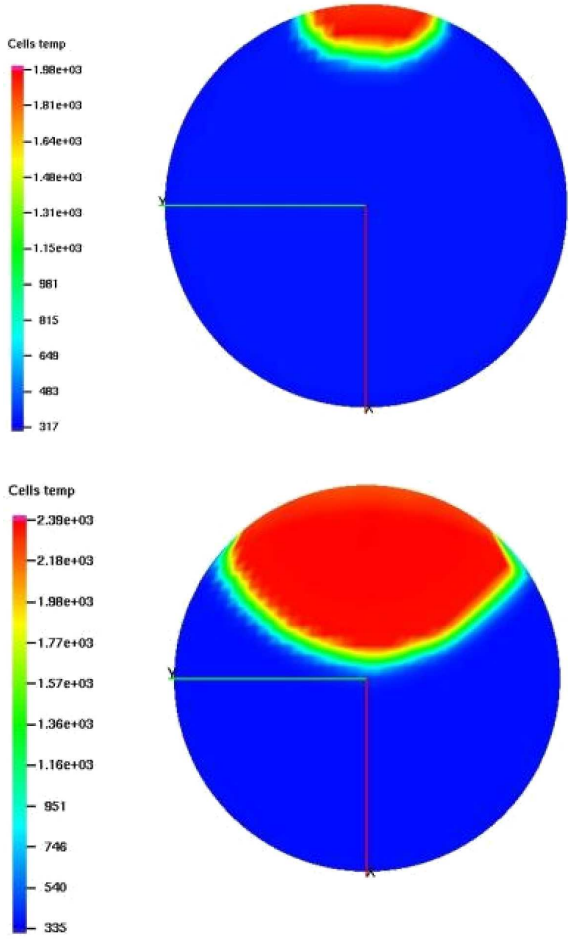


Fig. 11. Comparison of temperature distribution in the cross section at combustion of a) lean (left) and b) stoichiometric mixtures (right) at 34 ms after beginning of ignition

6. Test stand

Investigations on pressure changes during the lean mixture combustion in the main combustion chamber were carried out on the test stand presented in a rough outline in Fig. 12. The main combustion chamber of the constant volume was equipped with two small glass windows through which the flame propagation of the analyzed lean mixtures could be photographed by means of the Schlieren system.

The mixture was ignited in the pre-ignition chamber which was situated of the end of the redesigned spark plug filled with the rich mixture. The main combustion chamber had been filled with the lean mixture of the necessary equivalence ratio. It was also possible to initiate the flame directly in the main combustion chamber by electric spark discharge of the conventional spark ignition system. The cavity of the pre-ignition chamber was variable, that is, it was possible to use, one, two or three orifices for jets, the main diameter of the axial orifice was 2.5 mm, the lateral orifices 1.75 mm.

The volume of the pre-ignition chamber was 1.5 cm^3 and the volume of the main combustion chamber was 270 cm^3 with an 83 mm diameter. In the Schlieren system spherical mirrors of 122 mm focal length were used in the making of flame photographs for the certain time delays. Traces of the combustion pressures had been made using the oscilloscope connected to a special camera. After every charge the main combustion chamber and the pre-ignition chamber were emptied of combustion gases by means of a vacuum pump. Each test was repeated four times. It must be added that filling took place by means of rotameter. In order to protect the rotameter against damage by the combustion pressure the pre-ignition system was equipped with a safety check valve.

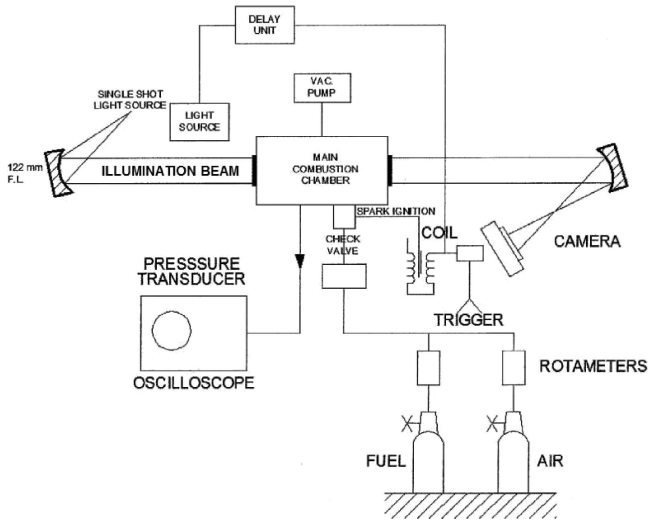


Fig. 12. Scheme of the test stand for pressure combustion and velocity analysis using the Schlieren system

7. Mode of filling up the main combustion chamber with a mixture of different equivalence air-fuel ratio

The main combustion chamber of a volume V_v containing air of atmospheric pressure, is coupled with propane-air mixture of the same composition as that in the pre-ignition chamber of the equivalence ratio $\phi = 1.95$. Hence, the quality of the mixture which is produced in the main combustion chamber decisively depends on the time lapse necessary for filling up the main combustion chamber. Whereas, after a certain time, depending on the volumetric flow rate of the mixture the main combustion chamber be filled with the rich mixture. Hence, it is based upon the definition of the equivalence ratio written as follows:

$$\phi = \frac{F/A}{(F/A)_s}, \tag{13}$$

where F – actual mass of fuel, A – actual mass of air, $(F/A)_s$ – stoichiometric ratio of fuel-air.

The equivalence ratio in the main combustion chamber can be determined as a function of the filling time. With reference to (13) particular components are determined as follows. The mass of air in the main combustion chamber is determined by:

$$A = V_v p_a. \tag{14}$$

Whereas, the mass of mixture flowing into the combustion chamber is:

$$m_m = V_m p_m. \tag{15}$$

The volumetric flow rate of the mixture V_m will be written as the sum of air and fuel volumetric flow rates

$$V_m = V_a + V_f. \tag{16}$$

After substitution of (15) and (16) into (13) and after transformations we get the approximate equivalence ratio of the mixture which flowed into the main combustion chamber as a function of the time

$$\phi(t) = \frac{V_m t \phi}{V_v \left(1 + \dfrac{p_a \phi}{L p_L}\right) + V_m t}. \tag{17}$$

This formula requires composition $\phi(t)$ which is written as follows:

$$t = \frac{V_v}{V_m}\left(1 + \frac{\phi p_a}{L p_L}\right)\frac{\phi(t)}{\phi - \phi(t)}. \tag{18}$$

Moreover, to obtain a required $\phi(t)$ this method of filling gave repeatable measurement results.

8. Comparison between combustion pressures initiated by the conventional ignition and by the jet ignition system

Examinations were carried out for the whole range of the equivalence ratio of an ignitable mixture. The experiment began with the lean mixture of the equivalence ratio $\phi = 0.7$ in the main combustion chamber and in the pre- ignition chamber was the rich mixture of the equivalence ratio $\phi = 1.95$. Further, an enrichment of the mixture above, $\phi = 1.95$, caused a decrease in the combustion pressure to a boundary case of the rich mixture at $\phi = 2.45$ when ignitability of the mixture was vanishing. The equivalence ratio of the mixture in the pre-ignition chamber was also changing in the range of $\phi = 0.7$ – 1.95. The highest value of the combustion pressure in the main combustion chamber occurred at the equivalence ratio $\phi = 1.95$.

The number of jets in the pre-ignition chamber through which the flames of the rich mixture penetrate from the pre-ignition chamber is the second factor influencing the value of combustion pressure. Examinations which were carried out with 1 and 3 jets confirmed their positive influence on the former increase in combustion pressure as well as a slight increase in maximum values. Figure 13 shows the traces of combustion pressures recorded on an oscilloscope. A more intensive increase in combustion is visible. For a mixture of composition expressed by $\phi = 0.7$ investigations were carried out on the influence of the number of ignition jets the traces of combustion pressures, when in the pre-ignition chamber the mixture was at the equivalence ratio $\phi = 1.95$. After carrying out traces of the combustion pressure for 1 and 3 jets for the comparison, the traces are shown in Fig. 13 as curves 1 and 2 respectively: curve 1–1 jet; curve 2–3 jets.

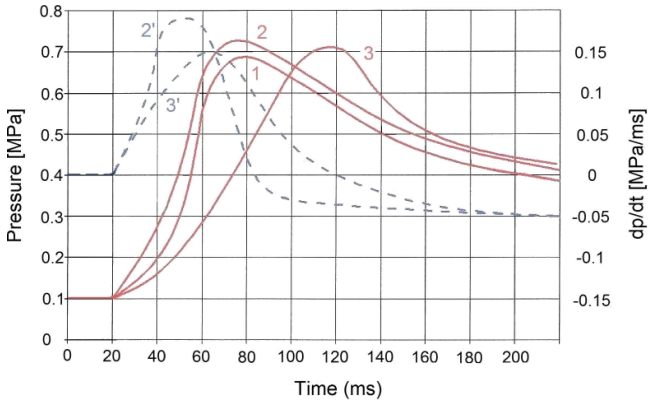


Fig. 13. Traces of combustion pressure of propane-air mixture: 1 – one jet flowing from the pre-ignition chamber at $\phi = 1.95$ to the main combustion chamber filled by a mixture at $\phi = 0.7$; 2 – three jets under the same conditions as in 1; 3 – flame initiated directly in the main combustion chamber filled by a mixture at $\phi = 1.05$; 2' – rate of pressure increase dp_2/dt; 3' – rate of pressure increase dp_3/dt

The difference between the maximum combustion pressures for three jets compared with 1 jet is about 7% but for this same maximum value of the combustion pressure using conventional spark ignition, also referred as "Flame Traversing the Charge" [7], it was necessary to fill the main combustion chamber with the mixture at the equivalence ratio $\phi = 1.05$.

Relative increments of pressure during combustion ignited by one jet-hole, three jet-hole according to combustion initiated directly in the main chamber are shown in Fig. 14. Curve (2–1)/1 presents the relative increment of pressure between combustion initiated by three jet-hole and one jet hole. The maximal increment of pressure equals over 40%. The relative increment of pressure between combustion initiated by one jet hole and initiated directly in the main chamber is shown by curve (1–3)/3. In this case the increment reaches 90%. The red curve (2–3)/3 shows the relative increment of pressure between combustion initiated by three jet hole and initiated directly in the main chamber. The maximal increment of pressure in this comparison equals 120%. Such a big relative increment of pressure during combustion initiating by pre-chamber holes promises that combustion time could be shorter.

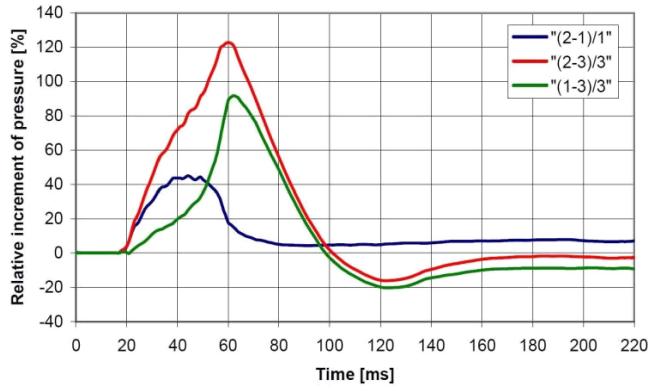


Fig. 14. Relative increment of pressure during combustion ignited by one jet-hole, three-jet hole according to combustion initiated directly in the main combustion chamber

9. Influence of Jet ignition on the traces of combustion velocity

The presented photograph in Fig. 15 shows the shape of the flame front in the case of mixture of $\phi = 0.95$ combustion initiated by the spark plug directly in the main combustion chamber at the combustion time equals about 70 ms after the spark ignition. The photograph in Fig. 16 concerns the same conditions of mixture but its ignition, induced by the spark plug, took place in the pre-ignition chamber with three holes. In results from a comparison of these two photographs in Figs. 15 and 16 that propagation velocity of the flame front in the case of the flame initiation in the main combustion chamber by jets ignition penetrating from the pre-ignition chamber is much higher. The photograph in Fig. 16 shows the shape of the flame front at a three jet ignition at $\phi = 0.7$ in the main combustion chamber. The photograph was taken 70 ms following the appearance of the spark. Having taken photographs every 70 ms it was possible to calculate the velocity of the flame propagation. Linear velocity of the flame comparing ignition of charge by three jet-holes with ignition directly in the main-chamber is higher about 21%.

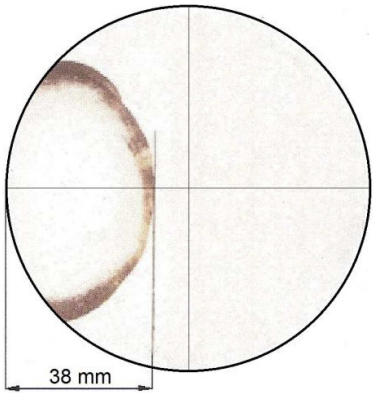


Fig. 15. The flame front of propane-air mixture initiated directly in the main chamber $\phi = 0.95$ with a time delay of 20 ms. Displacement of the flame marked in real value

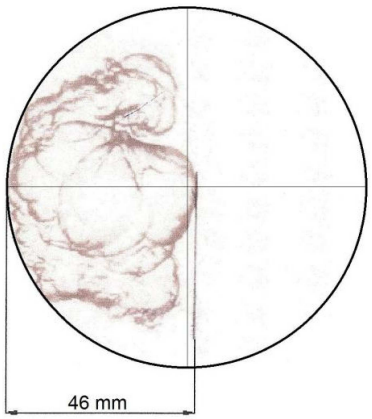


Fig. 16. The shape of the flame front initiated by three jets flowing from the pre-ignition chamber at $\phi = 1.95$ to the main combustion chamber at $\phi = 0.7$ with a time delay of 20 ms. Flame displacement marked in real value

It is necessary to emphasise that the central orifice for the jet was bigger than the other lateral one. Lateral jets were situated at an angle of 30°. In relation to the geometrical main jet their diameters were smaller: $d = 0.7$ dm, where d – diameter of the lateral orifice, dm – diameter of the main orifice. In the experiment which was carried out, the diameter of the main orifice in the pre-ignition system was used namely, $dm = 2.5$ mm. We may emphasize that when jets were situated at 30° to the main axial jet, the front of the flame was moving almost as a plane.

10. Conclusions

The presented paper introduces a mode of combustion using a jet ignition system. The experiment was carried out to compare the new results of combustion with the conventional "Flame Traversing the Charge". The results of this experiment are expressed as follows:

1. The relative increment of pressure between combustion initiated by three jet holes and initiated directly in the main chamber reaches the maximal value of 120%.
2. Combustion using the proposed jet ignition system is more efficient and linear velocity of the flame is about 21% greater. For that reason this system may be suitable for combustion in lean burn engines.
3. When the flame in the main combustion chamber is initiated by three jets it is possible to reach the plane front of the flame propagation. The increase in the volumetric flame velocity in this case reaches about 80 percent. This phenomenon would be very useful in high speed spark-ignition engines.
4. The results of the theoretical simulations of combustion initiated by one and three jet-holes confirmed very close results of the experimental test.

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