Experimental study of the flame propagation of gaseous fuel based mixture using optical visualisation

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Abstract. At this article presents experimental investigations carried out to determine the flame kernel propagation of gaseous fuel-air mixture under spark-ignition engine-like conditions. Various combustion processes taking place in an experimental combustion chamber are discussed. Consecutive shots of the development of the fuel flame front in a constant volume combustion chamber under different initial conditions are presented. Direct visual recording of an image of the combustion process is performed or Schlieren photography techniques are used. Modern types of spark plugs with different gaps in the entire price range are examined. CNG and LPG are used as gaseous fuels, since they are the main alternative fuels used in internal combustion engines for vehicles. Some of the results, such as pressure, maximum pressure and electric spark indicators, are shown as graphics. To calculate the speed of the flame propagation, specialised software processing the areas of the individual photos was used. The conclusions emphasize the results of relative air/fuel ratio, most favourable type of spark plugs and their gaps and location in the combustion chamber.

1. Introduction
Road transport is one of the biggest polluters of the environment, especially in urban areas. Reduction of carbon dioxide emissions is an issue of current concern in both Europe and the rest of the world. Electric vehicles are still not widespread due to their high price and low mileage coverage, and one of the solutions is to use internal combustion engines operating on gaseous fuel. In our country, the vehicle fleet consists mainly of vehicles, which are over 15 years old and they do not meet the modern environmental requirements. Their conversion to operate on gaseous fuel would help reduce carbon dioxide emissions, which they emit into the atmosphere. The use of lean air-fuel mixtures makes it possible to further reduce HC, CO and NOx emissions. The use of gaseous fuels instead of diesel fuel significantly reduces particulate emissions [1].

Spark plugs are an important element of internal combustion engine systems and the power, economic and environmental characteristics of the engines depend on their proper selection and technical condition [2, 3]. There are studies that provide information on the impact of the number of electrodes and their shape on engine performance [4, 5].

Gaseous fuels have been used since the discovery of internal combustion engines. They have been gradually replaced by liquid ones but due to the growing energy crisis and increasing environmental requirements at present, their importance and use greatly increases. Being a gaseous fuel, methane has different burning rate and flame spread manner compared to gasoline and diesel fuels. Methane has different oxidation properties compared to other hydrocarbons. More energy is needed to break the CH
chain of methane compared to that needed for higher hydrocarbons. It is hardly surprising that various experimental studies have proven that it is more difficult to ignite methane-air mixture than a mixture of air and other hydrocarbons [6]. Although various experimental methodologies have been developed and numerous previous measurements of laminar flame speed have been accomplished, small (3-5 cm/s) but still important differences exist [7].

The recording of the process provides great opportunities for studying the initial formation of the flame, its development, as well as its dependence on the turbulent motion of the fuel-air mixture and the strength of the spark [8]. As in constant volume chamber experiments can be performed on a Rapid Compression Expansion Machine (RCEM), to reproduce the operating and dynamic conditions encountered in an engine cycle, allowing for visualizations of the fuel injection and combustion processes through a transparent piston [9].

Traditionally, various methods of locating the position of the flame front have been proposed and used in the past. These mainly include the Shadowgraph, Schlieren and flame emission imaging techniques [10]. Popular optical accessible flame edges are shown in figure 1.

Studying the specifics of the combustion process would help reduce cycle variability in internal combustion engines, which is a significant problem, especially in single-cylinder engines [11]. When tests were performed in a constant-volume chamber to simulate exhaust gas recirculation (EGR) as in actual engine operations, it is possible to introduce different levels of inert gas [12].

Preliminary tests using the non-engine method can significantly reduce errors and facilitate the work of converting diesel engines to run entirely on gaseous fuels. Spark plugs are usually placed in place of the diesel injectors and very often it is not possible to mount them centrally in the engine's combustion chamber during this fuel change.

The aim of the present study is to perform comparative tests in a combustion chamber with specific dimensions corresponding to a real engine. Of particular importance are the data of the combustion process in lean air-fuel mixtures. The obtained results will help to properly design and adjust the fuel system of an engine converted to run on gaseous fuels.

2. Experimental setup

This report presents tests carried out in a constant volume combustion chamber. The test aims to determine the impact of the air/fuel ratio, type and location of spark plugs on the combustion process. One of the most commonly used method to study the combustion process is Schlieren photography technology. Internal combustion engines are characterised by their cyclic variability due to the random
nature of the combustion process. To improve the measurement accuracy, each experiment was performed 5 times and the results were averaged.

The experimental equipment is shown in figure 2. In the centre is shown the constant volume combustion chamber. The mixture is formed in a special mixing device, which is fed with fuel and air under specific pressure. A vacuum pump is installed to better clean the combustion chamber from the exhaust gases.

![Figure 2. Schematic diagram of the experimental setup.](image)

Based on the control of the pressure in the chamber, the required air/fuel ratio is regulated by releasing the fuel and air separately. After the combustion chamber is filled with mixture, a spark is ignited by a spark plug to the required initial pressure. Simultaneously with the spark delivery, the photographic system and measuring devices are activated. The pressure in the combustion chamber is registered by a pressure sensor. The photographs of the flame spread are obtained through Schilieren, using high-speed CCD camera EVANS-E2. The electronic shutter works with 1/10000 s. and the shooting speed is 200 frames per second.

The combustion chamber is shown in figure 3. The chamber diameter is 98 mm, and the chamber length is 24 mm. The processes in the combustion chamber may be examined by means of quartz glasses placed on both sides. Spark plugs may be placed both centrally and laterally. Several types of spark plugs manufactured by the Japanese company NGK are used in the current tests - normal, V-Power, and iridium ones.

### 3. Results and discussions

Figure 4 shows photographs taken directly with the camera of the flame front spread with propane fuel. An iridium spark plug located laterally in the chamber is used.

![Figure 4. Serial shots of the flame propagation in a propane-air mixture.](image)
Footage of the experimental study at different air/fuel ratios taken with the high-speed camera is shown in figure 5. The used fuel is methane. The movement of the flame front in the first 3 relative air/fuel ratios does not differ significantly, but at $\lambda = 1.1; 1.3$ and especially at $\lambda = 1.5$ the speed is visibly significantly lower. Different combustion processes are compared using area calculation software.

![Figure 5](image-url)  
*Figure 5. The development of the fuel torch in different relative air/fuel ratio $\lambda$.*

During the combustion of fuel-air mixture in the combustion chamber, the highest maximum pressure is obtained with the iridium spark plug (6.46 bar), followed by “V-Power” one (6.37 bar) and the lowest pressure is obtained with the normal spark plug (6.26 bar). Figure 6 shows the maximum pressure depending on the air/fuel ratio for the three types of spark plugs, which are located laterally in the constant volume combustion chamber.

![Figure 6](image-url)  
*Figure 6. The maximum pressure depending on the air/fuel ratio for three types of spark plugs.*
Figure 7 shows the pressure depending on the relative air/fuel ratio with an iridium spark plug on the side wall and methane fuel. It can be observed from the figure that there is big difference in the development of the combustion process when varying $\lambda$. The data from the series with the highest maximum pressure are selected.

The maximum voltage depending on the spark plug gap is shown in figure 8. When an iridium spark plug is used, the voltage is about 30% lower than that obtained in the use of normal one. The use of iridium spark plugs in lean fuel-air mixtures extend the life of the elements of the ignition system.

When the normal spark plug is located centrally, the maximum pressure (6.7 bar) is about 0.6 bar higher than in the side wall position at stoichiometric mixture. This difference is compounded if iridium spark plugs are not used.

![Figure 7](image1.png)

**Figure 7.** The pressure depending on the air/fuel ratio, iridium spark plug on side wall.

![Figure 8](image2.png)

**Figure 8.** The maximum voltage depending on the spark plug gap.
4. Conclusion
Experimental studies were performed in a constant volume chamber for the impact of certain parameters on the combustion process such as air/fuel ratio, type and location of spark plugs. Visual examinations complement the data taken from the pressure change in the chamber and expand the possibilities for studying the combustion process.

The major observations and conclusions of this study are:

- The depletion of air/fuel mixture above 1.2 leads to significant reduction in the speed of the flame propagation. The assessment of the possibilities for depletion of the fuel-air mixture gives us a direction for the use of higher degrees of compression ratio in the reconstruction of the real engine for work with gaseous fuels.
- The central spark plug location is better and makes it possible to achieve higher pressures in the chamber. If the design does not allow for such an arrangement, the performance can be improved by using iridium spark plugs.
- The maximum pressure in a methane-air mixture is obtained in slightly rich mixtures of relative air/fuel ratio 0.95. This permits to improve fuel economy and get maximum power from the respective engine without using rich mixtures.
- Iridium spark plugs are the best in terms of the combustion process and minimum load to the ignition system. They are also suitable for use in lean fuel-air mixtures.

The study will be expanded by comparing the rate of heat transfer and real motor tests.

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