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Obravnava motorja z notranjim zgorevanjem in vbrizgavanjem plinskega goriva

A Rapid-Compression-Machine Study of Gaseous Fuel Injection and Combustion

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V prispevku so predstavljene analize sistema za dovajanje goriva pri motorjih z notranjem zgorevanjem in neposrednim vbrizgavanjem plinskega goriva. Kratki primerni časi za vbrizgavanje plinskega goriva ter slabo prodiranje goriva in mešanje le-tega z okoliškim zrakom pomenijo velike probleme pri pravilnem vžigu in nadzorovanem zgorevanju mešanice. Ena izmed rešitev za olajšanje vžiga je uporaba manjše vžigalne predkomore. Vžig mešanice se tako začne že v predkomori, vroči in kemično dejavni zgorevalni plini pa nato pripomorejo k razbitju curka goriva v glavni zgorevalni komori, kjer poteka nadaljnje zgorevanje. Predstavljeni so rezultati raziskav vpliva oblike zgorevalnih komor pri uporabi neposrednega vbrizgavanja plinskega goriva na učinkovitost in ponovljivost vžiga. Raziskave so podprte z rezultati numeričnih simulacij postopka vbrizgavanja in mešanja plinskega goriva. Prikazano je, da lahko s predlaganim sistemom obidemo težave pri doseganju ponovljivega vžiga pri motorjih z neposrednim vbrizgavanjam plinskega goriva.
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(Ključne besede: motorji z notranjim zgorevanjem, vbrizgavanje goriva, goriva plinska, zgorevanje)

Rapid-compression-machine studies of an engine's combustion system with the direct injection of gaseous fuel were made. The very short time available for the injection, combined with the poor penetration and mixing of the gas jet with the surrounding air, caused the serious problems with combustion initiation. One of the solutions to facilitate the ignition seems to be the use of a small ignition prechamber. The ignition takes place within the prechamber and the hot, chemically active combustion gases saturate the gaseous fuel jet that enters the main chamber where the mixing and combustion processes are continued. The results of the investigations aimed at obtaining an efficient and repetitive ignition of the gaseous fuel jet are presented. Various versions of the combustion chamber were investigated. The investigations were supported by the results of numerical calculations of the injection and mixing processes. We concluded that this type of combustion system has the potential to overcome the difficulties in achieving the repetitive ignition of the gaseous fuel jet.
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(Keywords: internal combustion engines, fuel injection, gaseous fuels, combustion)

0 INTRODUCTION

The use of natural gas as a fuel for internal combustion piston engines has a number of advantages, which are well known to engine designers and researchers. There are many production engines where gasoline has been substituted by natural gas without major changes to the engine's operating mode but with a change in the fuel feeding system. In all such gas engines the gaseous fuel is delivered through the induction tube, and this means that the gas occupies a certain volume of the entire charge, decreasing the amount of air that is delivered to the engine cylinder during each engine cycle. This, in turn, tends to decrease the volumetric efficiency of the engine. To improve that efficiency, engine research centers try to find another solution, e.g., to develop the idea of injecting the gaseous fuel directly into the engine's combustion chamber. There are two ways to do this: to start the injection at an early stage of the compression stroke of the piston or to initiate the injection at the end of compression stroke. The former solution has already been applied to some production engines and it did not create major difficulties. The latter solution, however, still creates a lot of problems. The time available for the mixing of the injected gas with the air is very short, and the gaseous jet penetration in the combustion-chamber

Opomba uredništva: Znanstveni članki tujih avtorjev so lahko odslej samo v angleščini.

volume and its mixing with the air is weak. Compression-ignition of natural gas is practically impossible within the range of reasonable compression ratia; therefore, any type of forced ignition has to be used. If the mentioned problems were solved the combustion system with the late direct injection of natural gas would take advantage of the high compression ratio (on a diesel level) and still remain a spark-ignition system because of the necessary stabilizing role of the forced combustion initiation. The advantage of this type of combustion system is the reason that engine research centers try to remove the difficulties associated with the mixing and repeatad ignition of the charge. It is appropriate to mention that practically all the problems with natural gas storage, its supply to injectors and the action of the injector itself have already been solved. However, the in-cylinder processes in this type of combustion system still wait for the right organization.

1 THE GENERAL IDEA OF THE INVESTIGATED SYSTEM

To ensure the repeated ignition of the charge and, at the same time, to increase the mixing rate of the injected gaseous fuel with air and the combustion rate, the use of an ignition prechamber was proposed (Fig. 1). This prechamber is connected to the main chamber by an orifice. The orifice diameter is carefully designed to be a little bigger than the dimension of the gas jet's cross-section. During injection the main volume of the injection stream passes undisturbed to the main chamber and only a small external part of the jet is scrubbed off by the orifice edges. This portion of the injected gas remains in the prechamber, is mixed with the air and creates the portion of the charge that is ignited by the conventional spark plug. Since the shape of the gas jet remains basically unchanged the stoichiometry of the mixture in the prechamber should also be, relatively speaking, the same during each consecutive engine cycle. Therefore, there is a chance for repeatable and reliable ignition. Moreover, the charge in the prechamber is ignited when the injection is still in progress. The injected gas is then saturated with the combustion gases generated in the prechamber, which are then convected to the main chamber. The hot combustion gases containing chemically active free radicals create so-called multi-point ignition in the main chamber.

2 EXPERIMENTAL SETUP

The objective of this paper is to present the results of the preliminary investigations of the combustion system described above. The investigations were performed with the use of the rapid compression machine, described elsewhere, which makes it possible to visualize the in-cylinder phenomena [1]. The results of the experiments were compared with the results of calculations performed with the use of the KIVA3V computer code reduced to planar geometry [2]. The schematics of the experimental setup and combustion-chamber geometry are shown in Figures 2 and 3. The compression ratio was 10.8 and the piston velocity corresponded to an actual engine speed of 1600 rpm.

A Mitsubishi GDI injector was used for the gas injection. The injection pressure of the methane was 25 bar. The beginning of the injection, its duration and the ignition timing were adjusted and automatically controlled with an accuracy of 1 CA deg (crank angle degree). The reactions of the system investigated on the changes to following parameters were: beginning of the injection – (20-165 deg BTDC); injection duration – (15-50 CA deg); ignition timing – (10-30 deg BTDC).

Two prechamber geometries were investigated: without (Version I) and with the bypass channels (Version II).

3 RESULTS

As a result of the experimental investigations a number of pressure profiles and the corresponding series of framed pictures of the combustion processes was obtained. First, the development of the injected gaseous fuel jet was visualised to

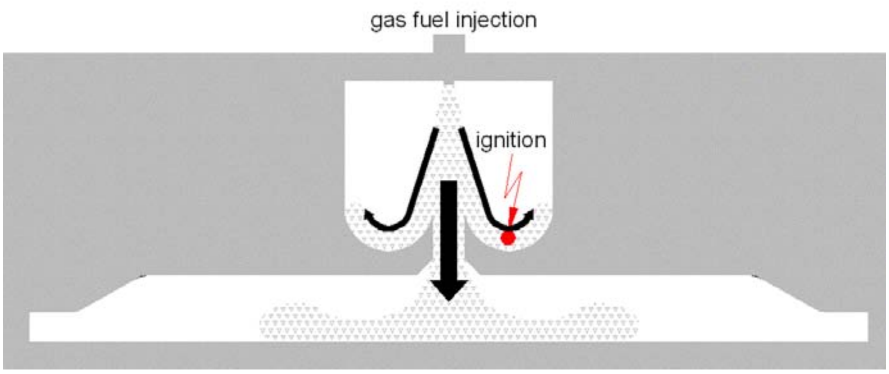

Fig. 1. *Schematic of the general idea*

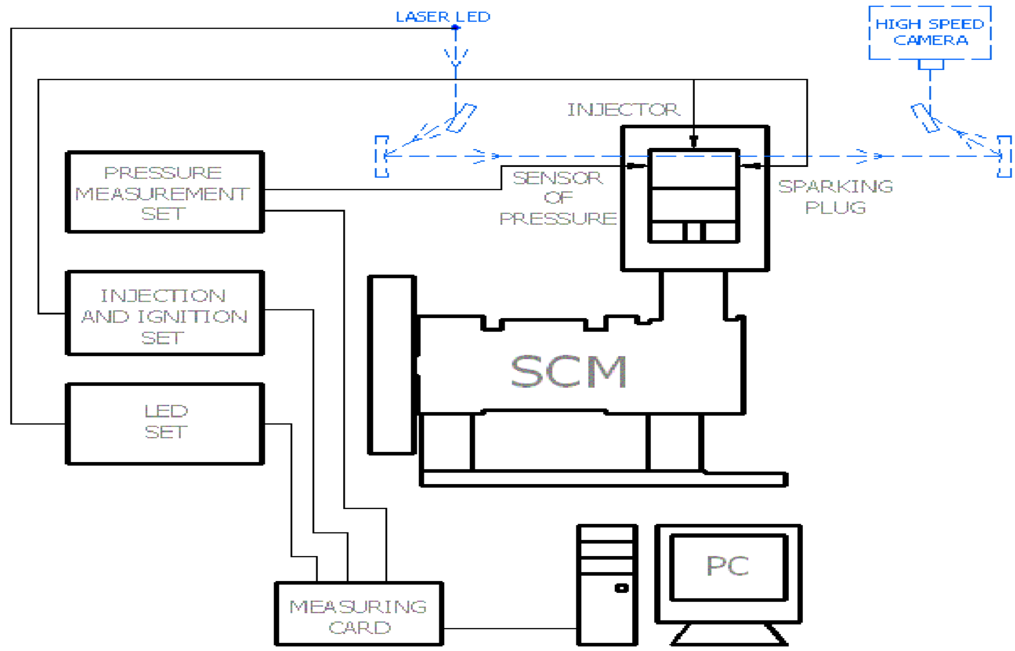

Fig. 2. *Schematics of the experimental setup*

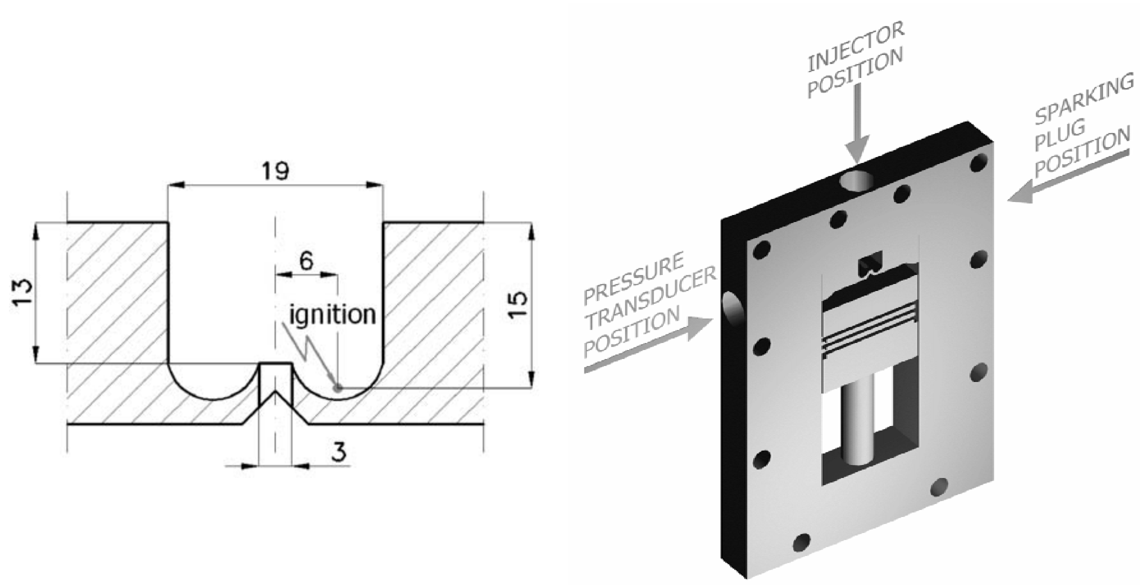

Fig. 3. *Combustion-chamber geometry*

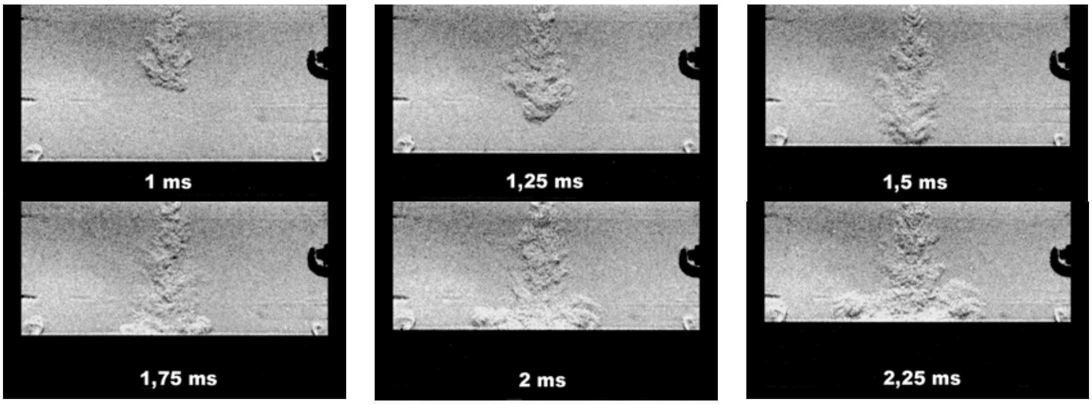

Fig. 4. *Visualisation of methane injection*

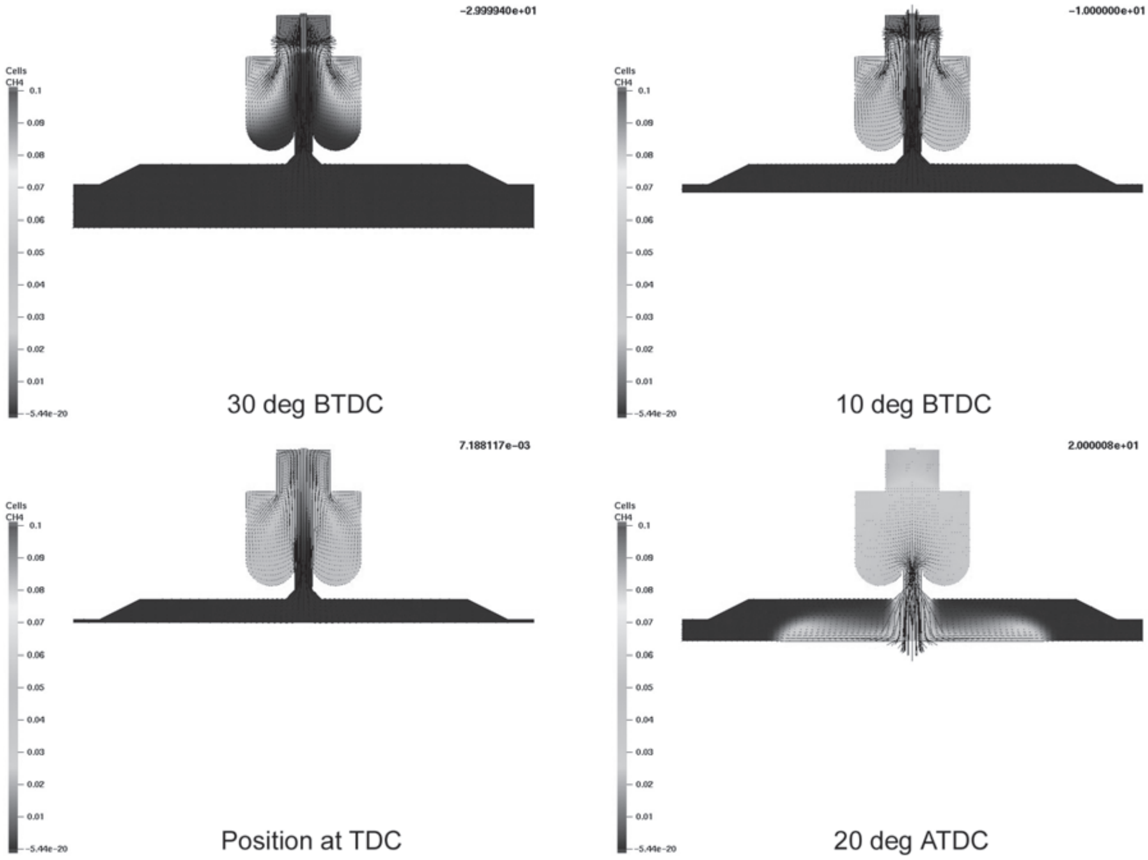

Fig. 5. *Velocity and methane-concentration distribution (prechamber geometry - version I)*

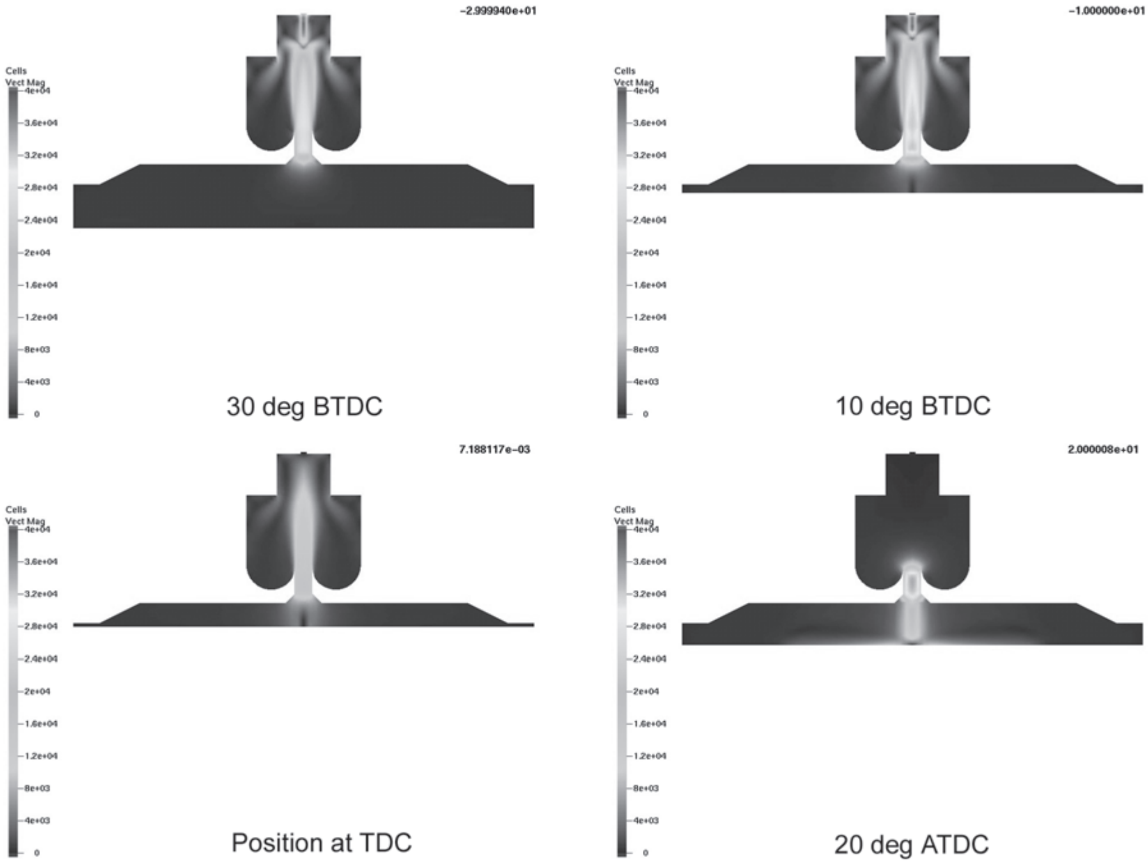

Fig. 6. *Velocity field (prechamber geometry - version I)*

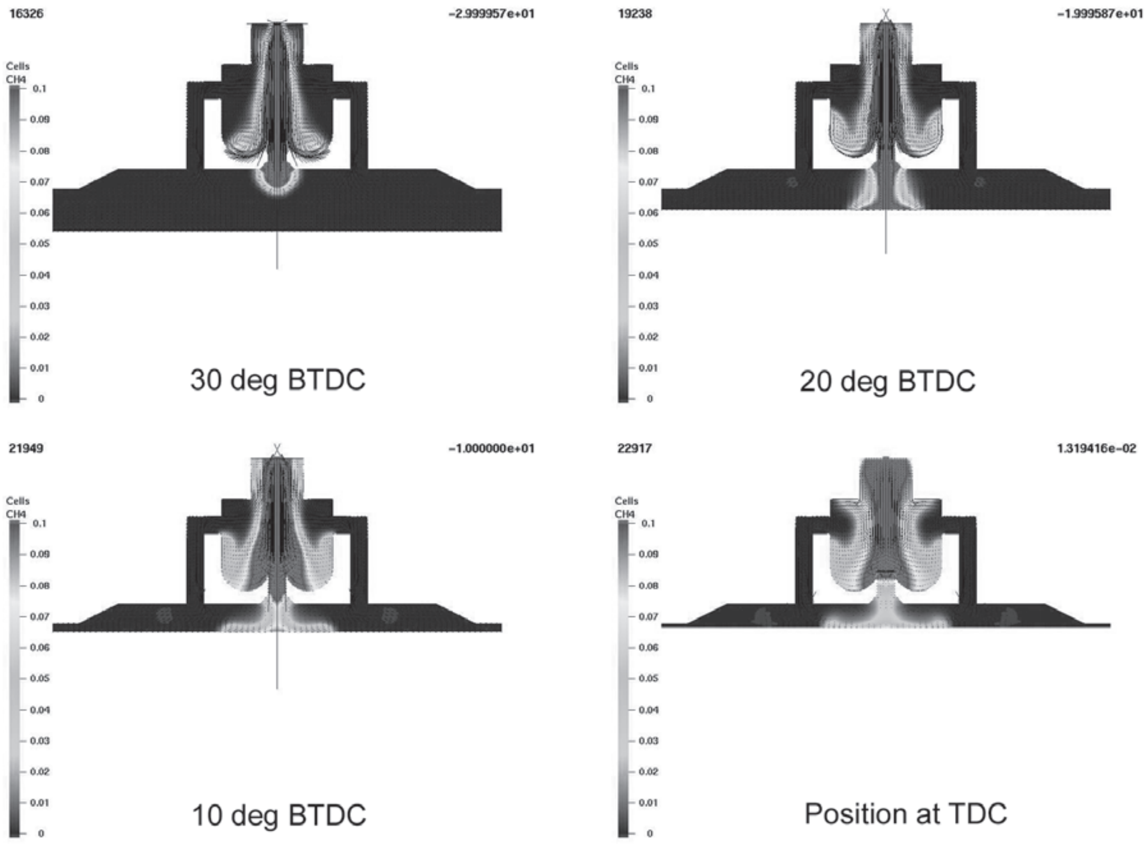

Fig. 7. *Velocity and methane-concentration distribution (prechamber geometry – version II)*

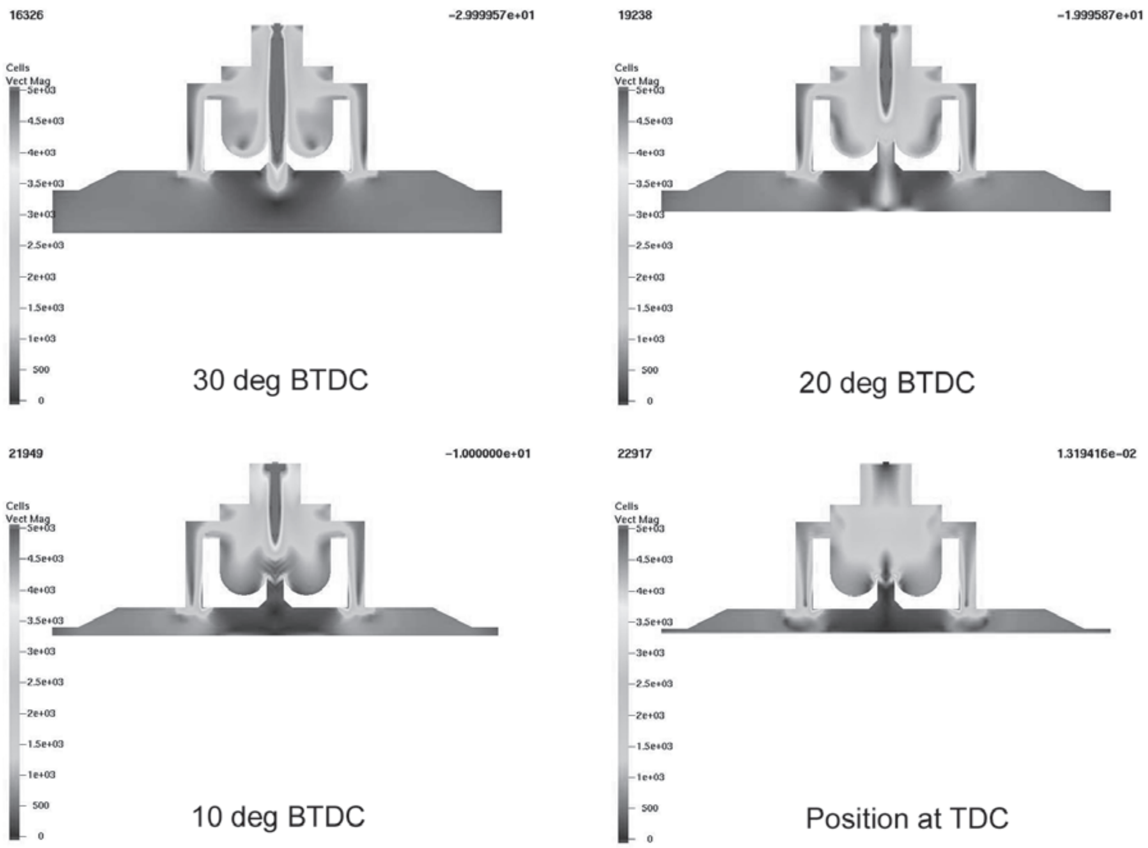

Fig. 8. *Velocity field (prechamber geometry – version II)*

determine its geometry and its ability to mix with the air. The framed pictures (obtained with the use of a schlieren technique) of the injection process are presented in Figure 4. The generation of the fuel jet was also carefully tested and the full characteristics of the jet (jet dimensions, fuel dose etc.) were determined.

Version I. Preliminary investigations of the combustion process in the chamber geometry presented in Figure 3 have shown that it is impossible to achieve the ignition of the charge under any set of system parameters. To find the reason for that the numerical analysis of the injection process was performed. The resulting gas-velocity distribution and the methane concentration in the prechamber allowed for the determination of the cause of the lack of ignition. The simple reason for this was that the injection took place during the end of compression stroke when the intensive flow of the air from the main chamber to the prechamber occurred in the orifice. The upstream velocity, of the air in the orifice was much greater than fuel jet velocity and therefore whole amount of the fuel injected remained in the prechamber. The mixture in the prechamber was much too rich side.
The demonstration of the velocity and methane-concentration distribution for this case is introduced in Figures 5 and 6.

Version II. To decrease the air velocity in the orifice generated by the compression it was necessery to increase the overall area of the channels connecting both chambers. The main orifice remained unchanged but two additional discharging channels were made. This drastically reduced the upstream air velocity in the orifice and the injected gaseous fuel was passing to the main chamber without difficulties. The motion of the gas in the chamber and the methane-concentration distribution in this case are presented in Figures 7 and 8. This change in the combustion-chamber geometry allowed for the repeatable ignition of the charge.

The framed pictures of the combustion process obtained from the experiments with the use of the rapid compression machine in the same combustion-chamber geometry are presented in Figure 9. First, the injected stream of fuel passes through the prechamber and its main portion enters the main chamber. The fuel gas scrubbed off the external part of the jet is mixed with the air in the prechamber where the flammable mixture is created. Then the charge in the prechamber is ignited and the combustion gases are intensively discharged to the main chamber due to the prechamber pressure rise and the action of the still injected gaseous fuel. Although it was observed that the overall pressure

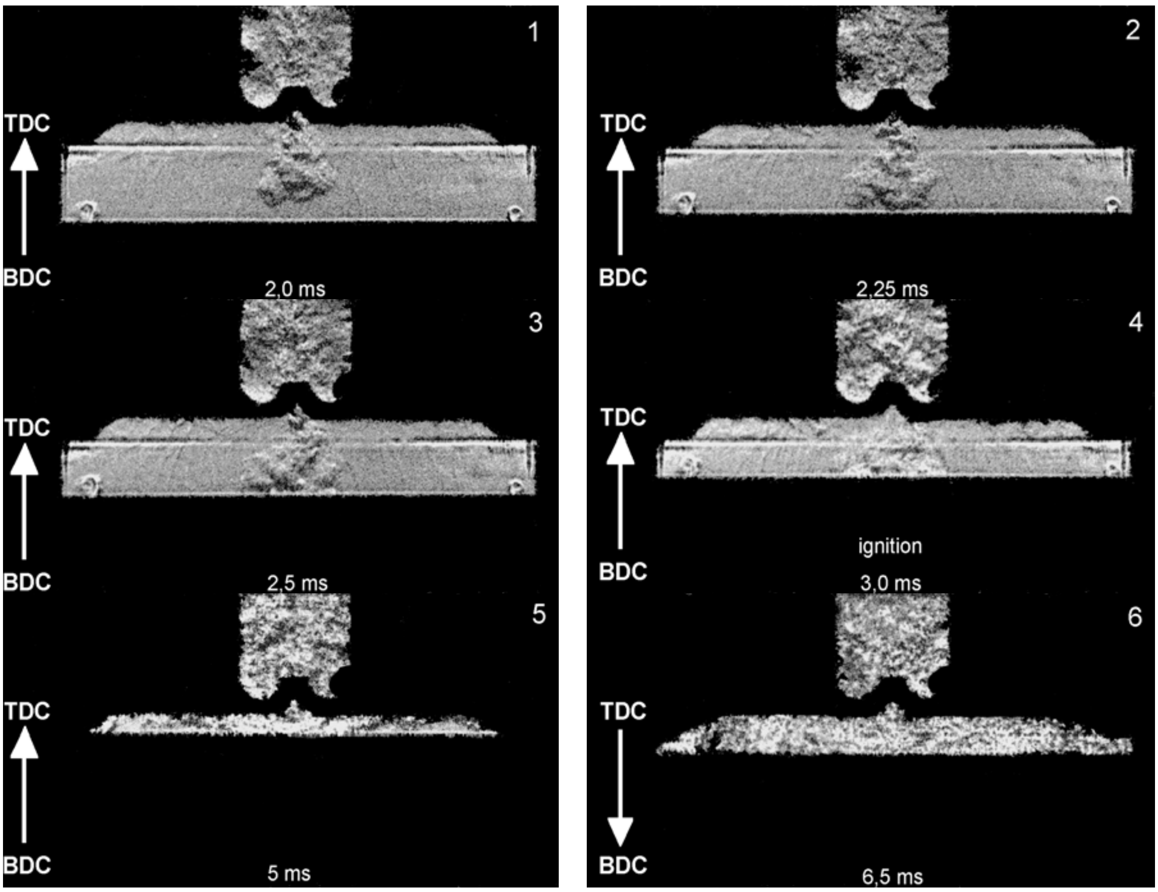

Fig. 9. *Visualization of the methane-combustion process (prechamber geometry – ver. II)*

rise rate in the combustion chamber is still not satisfactory, the difficulties with the ignition were removed.

The first frame in Figure 9 presents the methane jet 2 ms after the beginning of the injection. The methane jet enters the main chamber and the turbulence is generated in the prechamber. Frames 2 and 3 show the subsequent stages of methane injection. The ignition takes place during methane injection and this moment is presented in the fourth frame. Unfortunately, the high level of the turbulence in the prechamber is the reason why the combustion zone is hardly visible in the schlieren pictures. Moreover, the hot combustion gases generated in the prechamber are also ejected in the main chamber through the by-pass channels. The next frame was made just before TDC and shows the flame propagation process. The combustion has already been transferred in the main chamber but methane injection continues. The last frame taken after TDC presents the final stage of flame propagation, right after the end of the methane injection.

It is important to stress that the combustion-chamber geometry and dimensions were only designed for the rapid compression machine experiments and the aim of the presented investigations was to check whether of not the assumed idea of the system operation has been right. For the actual engine experiments the shape and proportions of the combustion chamber must be completely redesigned.

It is worth mentioning that the attempts to decrease the volume of the prechamber or to change the size of the orifice between chambers were not successful and they again caused serious problems with ignition.

4 SUMMARY

The major result of the investigation is that the proposed idea of a combustion system for engines with direct fuel-gas injection might be reasonable. The observed sensitivity of the system to its geometry and dimensions indicates that its application to the actual engine would require thorough optimization.

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