METHANE DIRECT INJECTION SYSTEM FOR SPARK IGNITION ENGINES – A NUMERICAL STUDY

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Abstract

A numerical study of the spark ignition engine with direct methane injection to combustion chamber is presented. Poor penetration of gaseous fuel jet and poor mixing with air in the engine cylinder together with very short time available for mixing create serious difficulties in choosing proper injection parameters and in arranging the combustion chamber geometry. The results of preliminary analysis showed that mixing process of methane with air is very complex. Direction of injection has a strong influence on mixing process and thanks to this a larger amount of fuel can be involved in mixing process. When fuel jet breaks up at the surface of combustion chamber wall gaseous fuel penetrates longer distance but mixing is not so efficient and layers with well-stirred mixture are surrounded with non-flammable mixture. Some amount of hydrogen added to methane can improve mixing and extends flammability limits so the zone of flammable mixture created in combustion chamber is much wider. The two-dimensional numerical simulations of gaseous fuel direct injection system were performed with the use of KIVA-3V computer code. The results of calculations allow for analysis of this system including spray structure, mixing process and flammable mixture zone position. Together with the related engine simulation this study create the base for the further numerical investigation of the engine combustion system with methane direct injection, which will be performed together with experimental research.

1. Introduction

Methane is considered as one of the alternate fuels for spark ignition engines because there are many resources of natural gas all-round the world and it can be even produced at dump from organic waste (biogas). Unfortunately biogas consists only about 60% of methane and the rest is a mixture of hydrogen, nitrogen and carbon dioxide.

Direct injection of the fuel has recently become very popular in SI gasoline engines. The main advantage of the direct injection system is that engine can operate in two modes: typical with high power output and economical with low fuel consumption. In typical mode engine operates almost like a typical SI engine - fuel is injected during intake stroke and nearly homogeneous mixture is created in the whole cylinder. The significant difference appears in the economical mode when much smaller amount of fuel is injected to the cylinder at the end of compression stroke, so the charge in cylinder is stratified and flammable mixture is located close to the spark plug. The economical mode allows for the reduction of: fuel consumption, amount of heat released, maximum temperature and pressure in cylinder, temperature of the exhaust gases and exhaust emission. Unfortunately special design of combustion chamber is necessary to create a stratified flammable charge close to cylinder head. Application of direct injection system to gas engines is not so easy because so many problems must be solved before it will be ready to use. The main problem is that the gaseous fuel jet does not penetrate the combustion chamber as good as liquid one. Moreover the process of gaseous fuel and air mixing is not as good as in the liquid fuel case. This two reasons cause that it is not easy to create flammable mixture close to the spark plug, especially in the economical mode when time available for mixing is short. Injection direction and timing together with injector position and combustion chamber geometry have significant influence on the mixing process and have to be investigated carefully.

Results of numerical analysis of the direct injection system are presented in this paper. This investigation was focused on the influence of fuel composition on mixing process and flammable mixture zone structure and position. All these results will be used in the future numerical and experimental investigations of the methane direct injection system in SI engines.

2. Computer modelling

All calculations were performed for two-dimensional mesh with average cell size of about 0.8 mm^2. Calculations were carried out on SGI Workstation and HP Xeon. The computer code KIVA-3V was used for the calculations and GMV post-processor was used for animations [1]. Three different fuel compositions were used: pure methane, pure hydrogen and mixture of methane and hydrogen (50%-50% volumetric), injection pressure was equal to 5 MPa. At the first stage of numerical investigation gaseous fuel was injected to open space (continuous injection). Analysis was focused on jet structure and fuel concentration was measured along injection axis. At the second stage gaseous fuel was injected to constant volume chamber with the shape similar to piston engine combustion chamber (with piston close to TDC). This stage was focused on mixing process under conditions similar to real engine.

3. Results and discussion

Animations were made from the results of calculations and they present fuel concentration and position of flammable mixture in considered area. Figures 1 to 3 show steady-state results for continuous injection of gaseous fuel to open space. Concentration of fuel (black colour represents pure fuel and white one represents pure air) at 50 μs (top row), 100 μs, 200 μs and 400 μs (bottom row) from the beginning of injection is presented in Figure 1. At the first phase of mixing the propagation of methane jet is significantly smaller than hydrogen one. The main reason is that hydrogen jet has about 3 times higher velocity at the injector nozzle than methane but methane jet has much larger inertia so the jet propagation equalizes soon. The second important difference between these two gases is the size of molecules. Hydrogen molecule is much smaller so mixing with air is better – hydrogen jet is the most dispersed one while methane jet is the most compact one.

Figure 2 presents charts of calculated fuel concentration vs. axial distance from injector nozzle. Methane jet propagates slower and mixing proceeds very slowly. Boundary of the jet is clearly visible and pure methane remains in the jet core for a long time. Better penetration of hydrogen jet allows for more effective mixing (fuel can mix with air in much larger volume) so the core with pure fuel is significantly shorter and fades quickly.

Figure 3 shows the flammable mixture position in a fuel-air mixing area. White colour represents non-flammable mixture (too rich or too lean). Flammable mixture zone is the widest for hydrogen jet. One of the reasons is of course more effective mixing but it is also caused by wider flammability limits for hydrogen-air mixture than for methane-air one. The mixture of hydrogen with methane brings quite good results. However mixing is slower than for pure hydrogen nevertheless propagation is faster than for pure methane and thank to this the area of mixing is larger. Flammability limits are wider than for pure methane so flammable mixture zone is created in larger area. Unfortunately it is still not big enough.

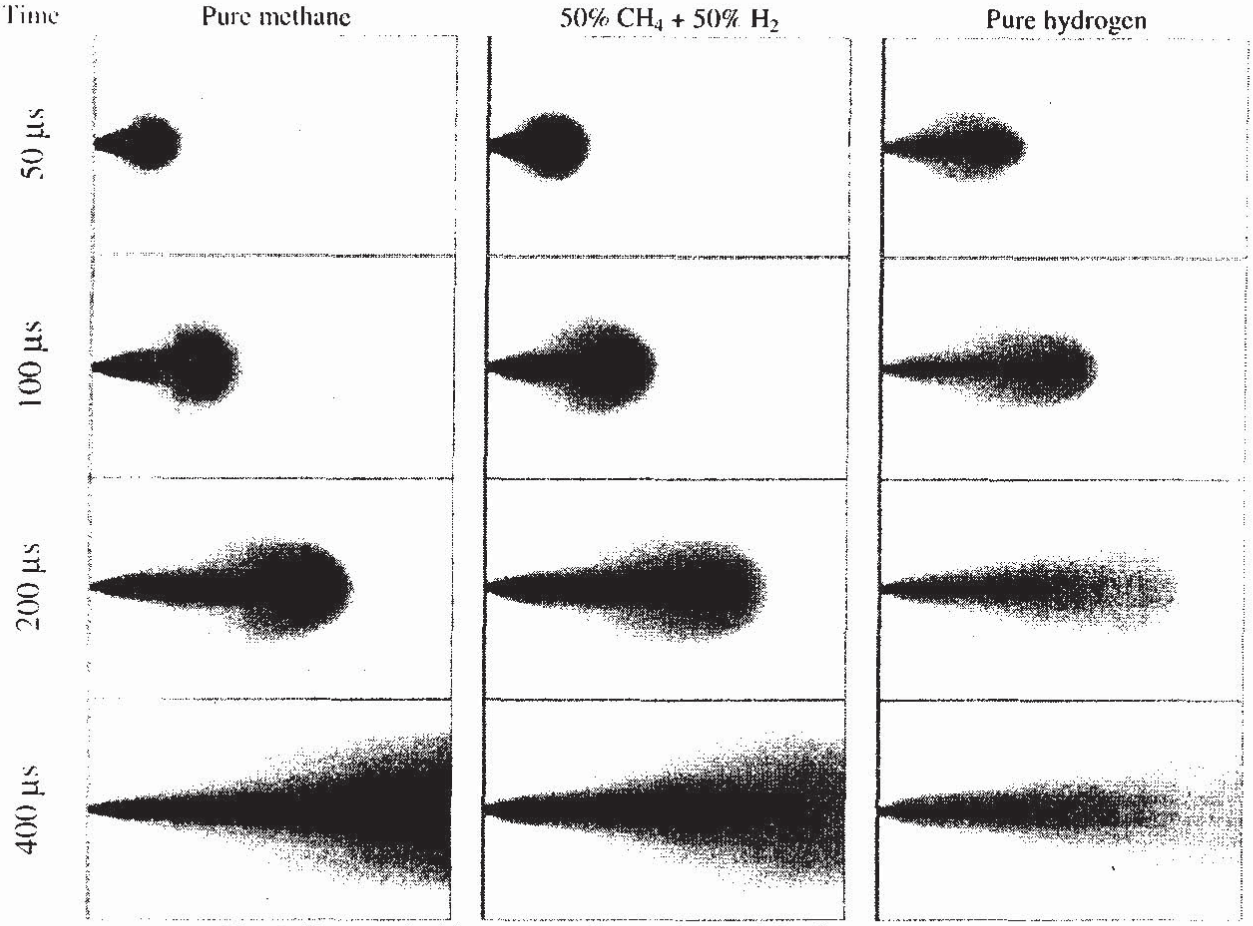

Fig. 1. Gaseous fuel jet structure for continuous injection to open space.

Figures 4 and 5 show the results for injection of gaseous fuel to constant volume combustion chamber. Time of injection was equal to 1ms. Initial pressure in the chamber was equal to 1.5 MPa - similar to pressure in typical SI piston engine cylinder close to the end of compression stroke. Figure 4 presents concentration of fuel (black colour represents pure fuel and white one represents pure air) at 0.50 ms (top row), 1.25 ms, 2.00 ms and 2.75 ms (bottom row) from the beginning of injection. In the first phase of injection gaseous jet breaks up on the chamber wall, spreads to the sides, reaches the sidewall very quickly and breaks up once again. These two break-ups intensify mixing process significantly. Mixing of methane jet is the slowest again. Even 2.75 ms after beginning of injection there is a large area with high concentration of fuel. Mixing of pure hydrogen proceeds very fast again so in this case mixture of fuel and air is well stirred.

Figure 5 shows flammable mixture position in constant volume combustion chamber. White colour represents non-flammable mixture (too rich or too lean). Flammable mixture zone is the widest for hydrogen jet – almost whole chamber is filled with the flammable mixture and there are large areas of stoichiometric mixture. It shows once again that mixing of hydrogen and air is more effective than mixing of methane and air. The mixture of hydrogen with methane brings quite good results again. Extended flammability limits create possibility to prepare flammable mixture in much wider area than for pure methane. This advantage allows for obtaining well-stirred mixture in cylinder and chamber shape can be less complex then for pure methane injection.

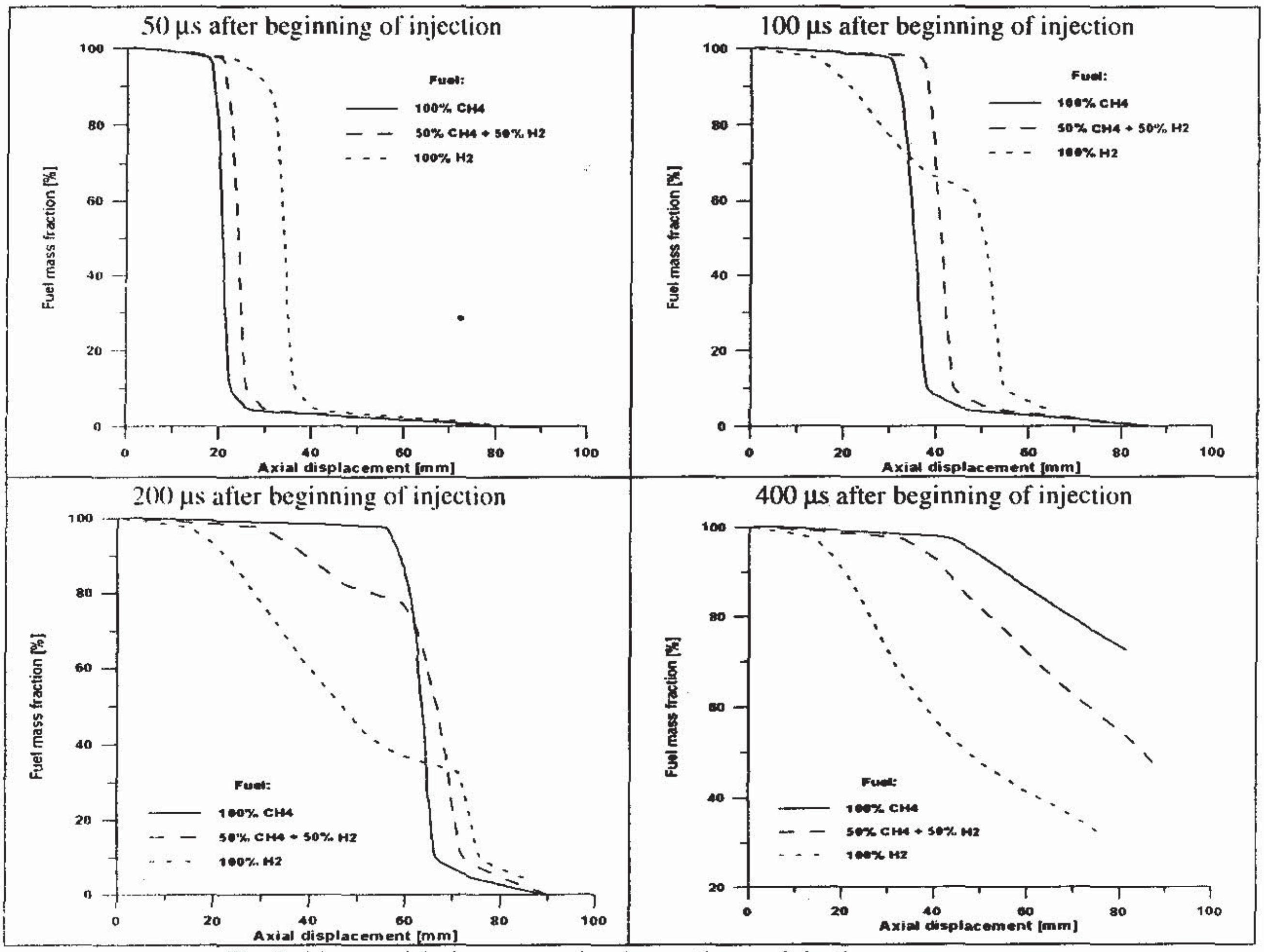

Fig. 2. Measured fuel concentration for continuous injection to open space.

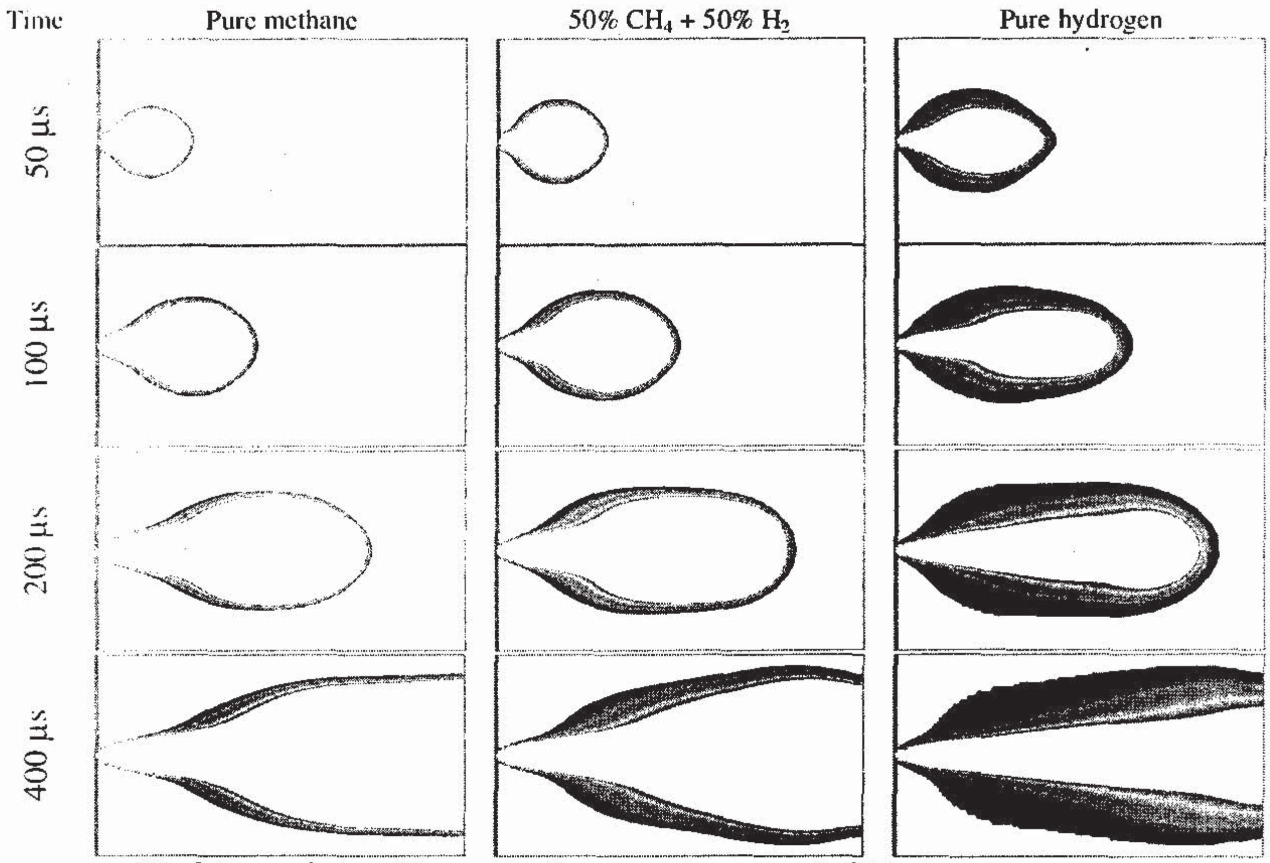

Fig. 3. The evolution of flammable mixture zone for gaseous fuel injection to open space.

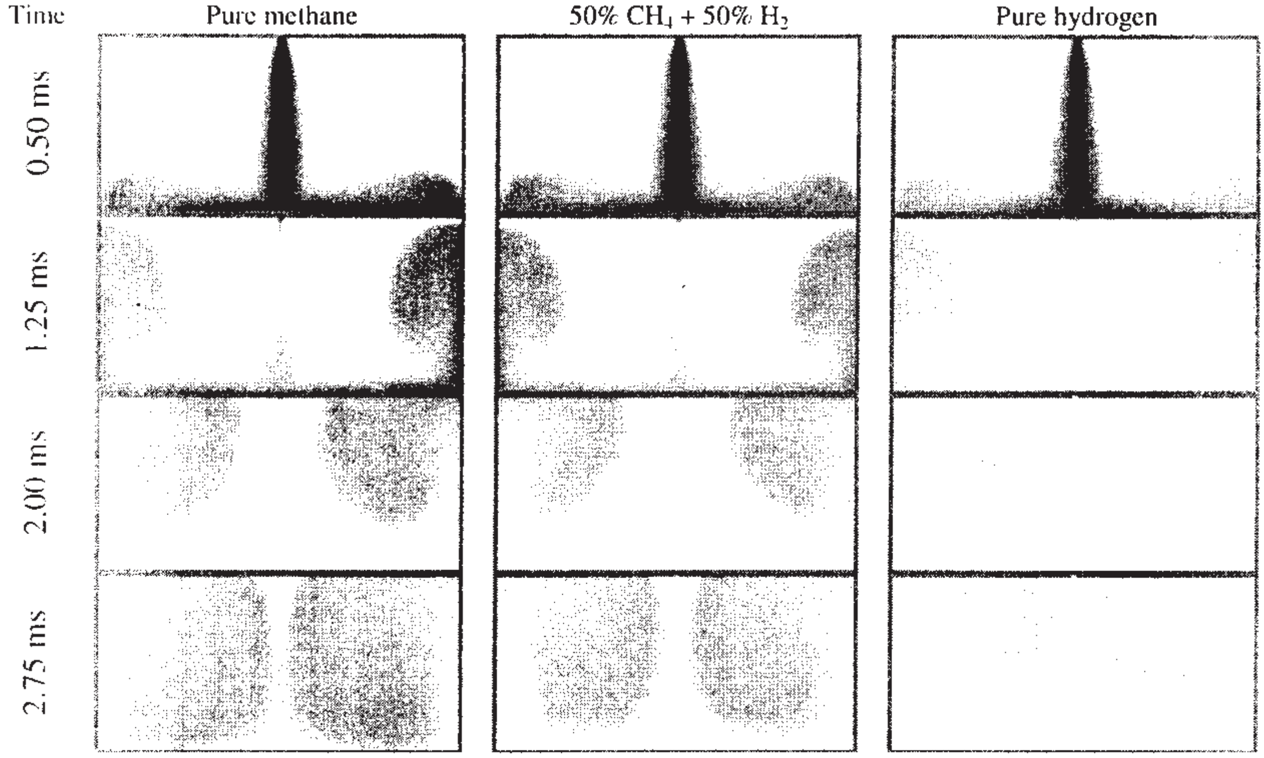

Fig. 4. Gaseous fuel jet structure for injection to constant volume chamber.

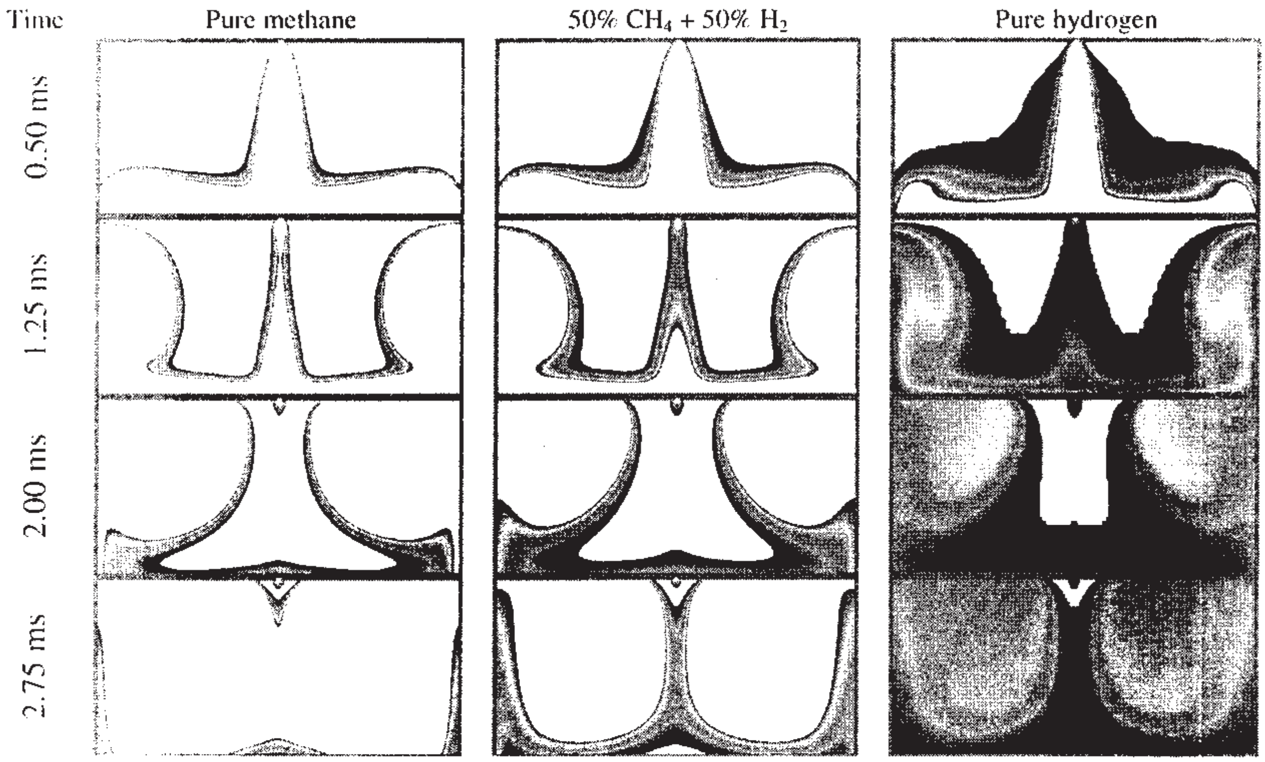

Fig. 5. Flammable mixture zone for gaseous fuel injection to constant volume chamber.

Conclusions

The results presented in this paper show that mixing process of gaseous fuel with air is very complex. First step of investigation has shown that hydrogen jet propagates faster and mixing process proceeds in much larger area. Methane jet mixing is not as good as hydrogen one so the core of pure fuel remains for a long time and well stirred area is very narrow. The second stage of research showed that mixing of hydrogen and air is more effective than for pure methane. Well-stirred mixture of hydrogen and air is created almost in the whole combustion chamber while well-stirred mixture of methane and air remains only close to the chamber walls. Extended flammability limits have also significant influence on preparation of flammable.

Mixture of methane and hydrogen brings quite good results. First of all mixing is more efficient than for pure methane, so design of combustion chamber shape can be not so complex. Secondly extended flammability limits decrease time between injection and ignition because flammable mixture appears is much wider area. All this advantages together with the fact that biogas includes mixture of methane and hydrogen make this solution worth more detailed investigation.

References

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