LEAN-BURN COMBUSTION SYSTEMS IN SPARK IGNITRON ENGINES: ADVANTAGES AND LIMITATIONS

Andrzej Gorczakowski, Jozef Jarosinski

Technical University of Lodz, Department of Heat Technology and Refrigeration
Stefanowskiego 1/15, 90-924 Lodz, Poland
tel.: +48 42 6312333, fax: +48 42 6367481
e-mail: jozef.jarosinski@p.lodz.pl

Abstract

Spark-ignited internal combustion engines are in the use for over130 years (first example was presented by Otto in 1876). The engine development is directed to more power, better efficiency and lower emissions. Mixture formation and in-cylinder motion are the main parameters of the combustion process improvement. One of the effective methods of engine development is lean combustion. Application of lean-burn combustion systems in spark ignitron engines has been proposed many times. Such systems have several important advantages in comparison with conventional systems. Lean-burn combustion makes possible engine operation at high compression ratio, equivalent to high thermal efficiency and at low emission of toxic components of the combustion gases. Lean-burn combustion is also a subject of serious limitations, requiring remedial steps. General limitations are introduced by a fall of the reaction rate, equivalent to increased time of combustion. Lean-burn combustion introduces also changes to flame structure: it contributes with increased flame thickness and with a rise of quenching distance. These changes influence limit conditions of spark ignition. The only solution omitting this threat might be obtained by replacing of a spark ignition by another ignition system or by application of a spark ignition system with increased distance between electrodes and with much higher ignition energy. Typical solutions rationalizing lean-burn combustion in engines are discussed in the paper and some limit conditions highlighted..

Keywords: *lean combustion, high compression ratio, combustion in swirl*

1. Introduction

Since the 1970-s, increasing costs of fuels and public concern for about clean atmosphere have forced research and development centers as well as manufacturers to change their design strategy. The analysis of the operation of the future engines showed that higher engine efficiency and a low level of exhaust emission can be obtained by combustion of a lean fuel-air mixture.

Reduced flame temperature and lower emission of nitrogen oxides accompany combustion of the lean mixture. Excess of the air promotes oxidation of carbon monoxide and unburned hydrocarbons. Besides, the lean mixture increases the effective expansion ratio, reduces the temperature gradient influencing heat transfer between the hot products and the cylinder walls and minimizes dissociation of the combustion gases. Lean mixtures can also tolerate a higher compression ratio.

However, lean-burn combustion creates some problems, because lean mixtures are not readily ignited, initial flame kernel is exposed to extinction and burning velocity is relatively small. Combustion systems with enhanced ignition, flame formation and its propagation must be applied, if lean combustion is to be reliably sustained. It was believed that such a role could be played by stratified charge combustion system.

A variety of stratified combustion systems were designed and investigated. Every of these combustion systems contained a small local volume of a rich mixture in an entire volume of the lean mixture. The rich mixture can be easily ignited and can burn completely together with the lean mixture during the remainder of a burning process. The local region with the rich mixture was organized in a special prechamber or as a part of a volume of the main combustion chamber. Combustion systems with prechamber were equipped with additional supplying systems. They were more reliable than other stratified systems, but at the same time much more complicated to be commercially acceptable. In late 70-ties lean combustion and improvement of engine efficiency were also obtained by inducing a strong swirling mixture and by increase of the compression ratio. This made possible to increase the charge mass flowing through the cylinder by the reduced role of the throttle. Ball-shaped or cylindrical combustion chambers with swirl were located in a cylinder head, below the exhaust valve [1] or in the piston [2], respectively. These systems unable burning of lean, homogeneous, air-fuel mixtures at relatively high compression ratios without knock. A combustion chamber with a strong swirl could extend the knock limit by at least 3 units [3-5].

Turning point in evolution of the engine combustion systems seems to be development of four-stroke, spark-ignition engines that are designed to inject gasoline directly into the combustion chamber. Recently many leading automotive companies have been developing and optimizing gasoline direct injection (GDI) combustion systems [6-8]. In these systems the deepest changes are introduced into the in cylinder flow field (formation of characteristic swirls) and air-fuel mixture formation structure. The weak point of such systems is their structural complexity and high production costs.

Recently in many research centers combustion systems operating in homogeneous charge compression ignition mode (HCCI) are developed. HCCI engines tend to operate at lean air-fuel ratios and at high compression ratio. In this system the fuel-air mixture is compression heated and self ignited at one or more points, similar to a conventional compression ignition engine (Diesel).

Let us characterize the basis features of lean-burn combustion system in spark ignition engines.

2. The most characteristic features of lean burn engine systems

2.1. High compression ratio

It was proved for the first time experimentally that it is possible to use high compression ratio in lean burn engine under high load in Fireball combustion system developed by M.S. May [1] and several years later in research work carried out by M.T. Overington [2] in laboratories of Ricardo Company. Schematics of both systems are shown in Fig. 1-2.

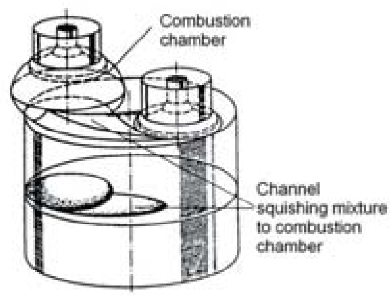

Fig. 1. Fireball combustion system with high compression ratio and high intensity squished swirl

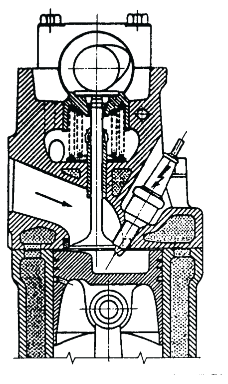

Fig. 2. Combustion system HRCC (High Ratio Compact Chamber) of Ricardo Company

Presented systems make possible to burn lean mixtures at high compression ratios (even to $\varepsilon = 16$). It was concluded as a result of analysis carried out in [2] that the optimal for piston engines comprassion ratio (from the point of view of engine efficiency) is a value from 14 to 16. Values of compression ratio higher than $\varepsilon = 16$ start to reduce overall engine efficiency because of increased mechanical losses.

One of the experimental engines was investigated in the Institute of Aeronautics. The engine was based on a four-cylinder direct-injection diesel engine Ford FSD 425. It operated in Otto cycle with high compression ratio $\varepsilon = 16$ and was fed by lean gasoline-air mixture The geometry of its swirl-generating inlet port and combustion chamber established high swirling ratio. The modification of diesel engine to Otto cycle was performed by replacing the fuel injectors with prechambers of similar shape, equipped with ignition plugs and catalytic inserts (Fig. 3). Swirling charge was ignited at relatively high compression ratio by a torch ignition from prechamber. The prechamber was fed with the same lean mixture as the main combustion chamber. The catalytic insert was used in prechamber for assistance to spark ignition. Application of a catalytic insert in a prechamber facilitated ignition, extended flammability limits and promoted clean combustion of a lean mixture in the main chamber.

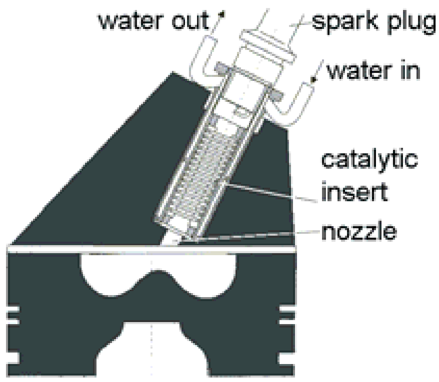

Fig. 3. Configuration of the prechamber and the main combustion chamber in modified engine FSD 425.

The engine worked in engine test bed under no throttled mode for several hundreds of hours with very lean mixture (the excess-air ratio was $\lambda = 1.6$). The engine efficiency was the same as in the original Diesel engine.

Also GDI systems work at elevated compression ratios. The leader of GDI technology Mitsubishi uses in his engines compression ratio $\varepsilon = 12.5$.

Much higher compression ratios are used in HCCI combustion systems, where flammable charge is compression heated up to a self-ignition temperature.

2.2. High swirling ratio

Swirl in the combustion chamber is introduced to burn lean mixture with increased compression ratio far from the knock limit [1-5]. In this chamber, the flame propagates in the field of centrifugal forces increasing with a radius. Under such conditions the flame surface takes the form of a cylinder (see Fig. 4).

Extensive experimental study of flame propagating in a mixture with rigid-body rotation was carried out in [4]. The experiments were performed in a closed cylindrical vessel with transparent walls. The effect of the rotation rate on flame propagation was investigated. The flame propagating in a swirling mixture is axisymmetric. At the beginning it propagates from the ignition point in axial direction. After touching the side-wall of the cylindrical vessel the flame starts to propagate in radial direction. The axial propagation velocity of the flame increases and the radial propagation velocity decreases, with the rise of the rotation rate.

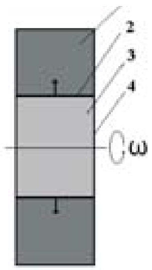

Fig. 4. Side view of flame propagating in a rotating cylindrical vessel. 1-flammable mixture, 2-flame, 3-combustion gases, 4-front wall of the combustion chamber

It was found that combustion in swirling mixture with moderate rotation rate is advisable from the point of view of well ordered burning and extension of the knock limits. In swirling mixture combustion processes are controlled by centrifugal forces. Light combustion gases flow in the direction of the rotation axis, while heavier fresh mixture remains outside. This model promotes laminarization of combustion and reduces knock limits [3, 9]. If the mixture in swirling flow is accidentally ignited by hot spots the most probable flame behaviour is similar to that shown in Fig. 5.

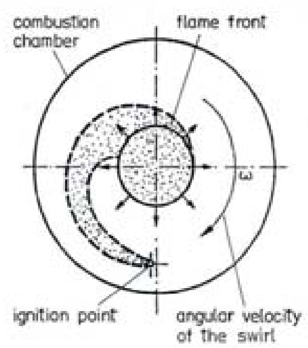

Fig. 5 Character of flame propagation initiated far from the axis of rotation

The flame initiated at the ignition point propagates first in a form of narrow path to the centre of the rotation and then outside as a cylindrical surface, with propagation velocity approaching the laminar burning velocity.

Swirls are commonly used in lean-burn combustion systems, but their spatial orientation for different systems is different.

2.3. Methods of mixture formation: stratified or homogeneous

Combustion systems with both methods of mixture formation (stratified and homogeneous) are used. Stratified charge combustion was recommended in the early stage of lean combustion systems with moderate compression ratio. Charge stratification with rich spot near a spark plug improved the initial combustion conditions, producing a strong flame kernel and intensifying flame propagation. Three methods for stratification are commonly referred to as wall guided, air guided, and spray guided [8]. The most promising is the spray guided system, which utilizes spray targeting directly at the spark plug. In this case the spark ignites a passing region of high fuel concentration. Developed in 90-ties GDI systems followed this concept of combustion initiation (Fig. 6). Important role in formation of stratified charge in GDI play modern, highly developed injection systems.

In some of the combustion systems, with high compression ratios, such as Fireball [1], HRCC [2] or that applied in modified FSD 425 engine [5] lean homogeneous mixture was successfully used. In these systems flammable charge is heated by compression to elevated temperatures. This seriously reduces requirement of high ignition energy and makes ignition easy.

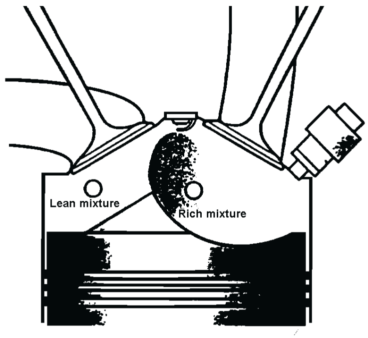

Fig. 6 Local mixture formation near spark plug in GDI combustion system

Also HCCI combustion systems tend to operate at very lean homogeneous air-fuel mixtures. The most perspective method of homogeneous mixture formation seems to be early fuel injection in the intake stroke (during moderate and high-load conditions).

2.4. Ignition systems

In majority of the early developed stratified combustion systems a prechamber with rich mixture was used for ignition. Initiation of lean mixture combustion in the main combustion chamber was made by a jet of burning gases from the prechamber (torch ignition). The week point of such systems is their structural complexity and reduced reliability. The catalyst-aided ignition and combustion proposed in [5] played the same role in the whole process as the stratified charge combustion system, but was significantly simpler. The prechamber was an integral part of the combustion system. It comprised no moving elements or mechanisms and was fed with the same flammable mixture as the main combustion chamber. This kind of ignition was very effective.

In gasoline direct injection systems spray of fuel flows directly at the spark plug (see Fig. 6). The fuel-air mixture in HCCI is compression heated and auto-ignites in a similar way like in Diesel engine. However, in contrast with Diesel engine, the flammable mixture in this system is homogeneous. As a result of this, combustion can be controlled exclusively by manipulation of the thermal state of the combustion chamber. This can be done through intake air heating or inducting some amounts of hot combustion gases. However, this strategy cannot be effective in transient engine operation. The proper solution to coctrol combustion of lean homogeneous mixture can be spark-assisted compression ignition system. The combination of compression heating and spark process can ensure reliable auto-ignition maintaining a method for controlling combustion timing. Application of corona discharge for combustion control of HCCI systems is also considered [11, 12].

3. Conclusions

Reported here technological solutions of lean burn engine systems present advetages and disadventages relating to performance, emissions, and efficiency. Most likely the next generation engine will be built as a multi-mode engine that combines selected existing solutions. Stratified charge stands a chance to be used at light loads, where pumping losses are considerable, but emission of NO_x is relatively low. Spark-assisted homogeneous charge compression ignition can be employed at moderate and high-loading conditions, with ability to reduce NO_x emissin using the 3-way catalyst.

Further development of the multi-mode engine depends on the advancement of engine technology. More sophisticated and reliable injection systems are needed, particularly under stratified conditions. Also new intake and exhaust valve actuation systems should be developed to better combustion control mechanisms. Progress in technology will contribute to the rise of spark-ignition engine efficiency and can make it more competitive than a compression-ignition engine from the point of view of emission and performance.

Acknowledgements

This work was sponsored by the Marie Curie ToK project from the 6th FP contract No MTKD-CT-2004-509847 and by the Ministry of Education and Science under the project No. 4T12D 05129.

References

[1] May, M. S., Spinnler, F., „*Betriebserfahrungen Hochverdichteten Ottomotoren nach dem May Fireball-Verfahren*", MTZ, No. 6, 39, pp. 243-246, 1978.
[2] Overington, M. T., „*Gasoline Engine Combustion - The High Ratio Compact Chamber*", SAE Technical Paper Series 820166, 1982.
[3] Gryglewski, W., „*Influence of Rotation Rate on Combustion in Spark Ignition Engine*", PhD Thesis, Lodz, Poland, 1995.
[4] Gorczakowski, A., Jarosinski, J., „*The Phenomena of Flame Propagation in a Cylindrical Combustion Chamber with a Swirling Mixture*", SAE Technical Paper Series 2000-01-0195, 2000.
[5] Jarosinski, J., Lapucha, R., Mazurkiewicz, J., Wojcicki, S., „*Combustion System of a Lean-Burn Piston Engine with Catalytic Prechamber"*, SAE Technical Paper Series 2001-01-1186, 2001.
[6] Takagi, Y., „*A New Era in Spark-Ignition Engines Featuring High-Pressure Direct Injection*", Twenty-Seventh Symposium (International) on Combustion, The Combustion Institute, pp. 2055-2068, 1998.
[7] Kuwahara, K., Ueda, K., Ando, H., „*Mixing Control Strategy for Engine Performance Improvement in a Gasoline Direct Injection Engine"*, SAE Technical Paper 980158, 1998.
[8] Zhao, F., Lai, M. C., Harrington, D. L., „*Automotive Spark-Ignited Direct-Injection Gasoline Engines"*, Progress in Energy and Combustion Science, 25, pp. 437-562, 1999.
[9] Zawadzki, A., Jarosinski, J., „*Laminarization of Flames in Rotating Flow",* Combust. Sci. Technol., 35, pp. 1-13, 1983.
[10] Chomiak, J., „*Private communication"*, 2007.
[11] Bellenoue, M., Labuda, S., Ruttun, B., Sotton, J., „*Spark Plug and Corona Abilities to Ignite Lean Methane/Air Mixtures"*, Proceeding of the ICDERS, Montreal, 2005.

"The author's reward was sponsored by Society of Collective Management of Copyrights of Creators of Scientific and Technical Works KOPIPOL with registered office in Kielce with duties obtained on the ground of the art. 20 and art. 20^1 of law on copyrights and related rights."