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An analysis of efficiency and exhaust emission of the gasoline spray-guided engine

Abstract: A combustion system of spark ignition engine, which utilizes spray-guided mixture formation enables combustion of extremely lean mixtures. High rate of mixture stratification results in reduction of fuel consumption and exhaust emission in comparison to homogeneous charge combustion.

This study presents results of research of the gasoline spray-guided spark ignition engine. Experiments were performed on the BMW N43B20 engine equipped with a high-pressure gasoline injection system with piezoelectric injectors. Research was done with the use of two methods of mixture formation; preparation of homogeneous charge and stratified charge. The engine was operated at whole range of rotational speed and load. Operation in the stratified charge mode showed 20% increase of thermal efficiency versus the homogeneous charge in the range of low and middle engine load and rotational speed. Additionally, fuel consumption and exhaust emissions were analyzed at variable air excess ratio.

Key words: *gasoline direct injection, spray-guided*

Analiza sprawności oraz emisji spalin silnika benzynowego z tworzeniem mieszanki za pomocą strugi wtryskiwanego paliwa

Streszczenie: Systemy spalania w silnikach o zapłonie iskrowym, które wykorzystują tworzenie mieszanki w cylindrze za pomocą strugi (ang. spray-guided) umożliwiają spalanie bardzo ubogich mieszanek. Znaczny stopień uwarstwienia ładunku pozwala na obniżenie zużycia paliwa oraz emisji toksycznych składników spalin w porównaniu do silników spalających mieszankę homogeniczną.

W niniejszej pracy przedstawiono wyniki badań silnika benzynowego o zapłonie iskrowym z tworzeniem mieszanki za pomocą strugi wtryskiwanego paliwa. Eksperymenty zrealizowano na silniku BMW N43B20 wyposażonym w układ wysokociśnieniowego wtrysku benzyny wykorzystujący wtryskiwacze piezoelektryczne. Badania przeprowadzono przy dwóch sposobach tworzenia mieszanki; przygotowaniu mieszanki homogenicznej, oraz przy tworzeniu mieszanki uwarstwionej. Badania prowadzone były w pełnym zakresie prędkości obrotowej i obciążenia silnika. Praca silnika w trybie spalania ładunku uwarstwionego pozwoliła na wzrost sprawności cieplnej o 20% w porównaniu do spalania mieszanki homogenicznej w zakresie małych i średnich prędkości obrotowych i obciążeń. Ponadto przeprowadzono badania zużycia paliwa oraz emisji toksycznych składników spalin przy zmiennym współczynniku nadmiaru powietrza.

Słowa kluczowe: *bezpośredni wtrysk benzyny, tworzenie mieszanki za pomocą strugi*

1. Introduction

Homogeneous charge spark ignition (SI) engines with mixture formation outside cylinder are characterized by a number of imperfections. Homogeneous charge combustion and demand for stoichiometry result with limitations of further development of these combustion systems. In other words, classical spark ignition engines are not able to fulfill future legislations concerning fuel consumption and exhaust emission. The main disadvantages of homogeneous charge SI engines are [1, 13]:

a) Throttling of the engine at low loads and resulting pumping losses,
b) Propensity for knocking combustion which does not allow for increase of compression ratio [7],
c) Combustion of stoichiometric air-fuel mixture due to operation of 3-way catalytic converter,
d) Significant emission of unburned hydrocarbons due to the cold walls effect,
e) Significant emission of carbon monoxide due to combustion of stoichiometric mixture.

Combustion of stratified mixture allows to avoid limitations mentioned above. As a result of increased overall air excess and reduced throttling, pumping losses are minimized, thus improving thermal efficiency of the engine by 10%. Following 2% of efficiency can be gained via lower thermal losses [2]. Additionally, possibility to increase compression ratio results in efficiency improvement of about 3% [4]. Stratified charge allows for reduction of hydrocarbons emission versus homogeneous mixture. However benefits in NO_X emission depend on the utilized combustion system and exhaust gas re-circulation (EGR) rate [6, 10].

Combustion systems in direct injection spark ignition (DISI) engines can be divided into three groups, depending on a mechanism, which determines in-cylinder mixture formation [10]. In-cylinder movement of the rich mixture cloud can be forced by piston shape or fluid motion [8, 12]. The third mixture formation principle is based on the use of injected fuel spray dynamics (spray-guided system) [11]. In this combustion system spark plug and fuel injector are positioned in the combustion chamber in direct proximity, and spark discharge takes place shortly after start of injection.

In this paper experimental investigation of the gasoline spark ignition engine with spray-guided mixture formation system is presented. Comparative analysis of fuel consumption in two modes of the engine operation was done. In the first case the engine was operated in stratified, lean mixture mode, in the second case engine was fed with stoichiometric, homogeneous charge. Influence of air excess ratio on fuel consumption and emission was also analyzed. Working cycles for the two combustion modes were compared as well.

2. Experimental test stand

The object of the research was 4-cylinder BMW engine type N43B20 AY. The engine is equipped with direct gasoline injection and spray-guided mixture formation system. Table 1 presents technical data of the engine.

Table 1. Technical data of the N43B20 AY engine

No. of cylinders	4
Swept volume	1995 cm^3
Bore	84 mm
Stroke	90 mm
Compression ratio	12
No. of valves	4
Maximum torque	190 Nm
Rotational speed at maximum torque	4250 rev/min
Rated power	105 kW
Rotational speed at rated power	6000 rev/min
Maximum rotational speed	7000 rev/min
Fuel injector	Piezoelectric, outwardly opening
Fuel pressure	100…200 bar (5 bar)

The fuel injector and the spark plug are located in central part of the combustion chamber. The intake manifold and the intake ports are shaped to provide tumble in-cylinder air motion. Combustion chamber cross-section is presented in Fig. 1.

At the factory settings of the engine management system, it realizes three modes of operation, depending on engine load. Between idle load and IMEP approximately 0.6 MPa stratified charge is created. In this range overall air excess ratio (λ) reaches value of 2.7. Two fuel injections occur directly before spark discharge. At middle load split fuel injection provides partially stratified mixture. The first injection (60% of fuel mass) is applied in the intake stroke and the second dose of fuel is injected before ignition. In this mode of operation air excess ratio is below 1.5. Further increase of engine load results with homogeneous and stoichiometric charge combustion. Whole mass of fuel is introduced into the cylinder during the intake stroke, however with split injection technique. At rotational speed exceeding 4000 rev/min homogeneous charge is created in the whole range of engine load.

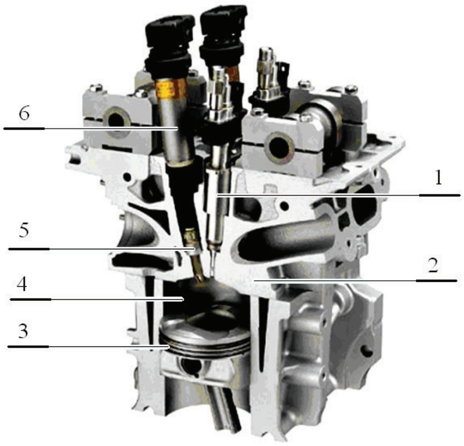

Fig. 1. Combustion system of the engine N43B20 AY; 1 – fuel injector, 2 – engine head, 3 – piston, 4 – combustion chamber, 5 – spark plug, 6 – ignition coil [3]

Fuel is applied into the cylinder with the use of piezoelectric injector. The outwardly opening injector creates hollow cone fuel spray. At homogeneous mixture injection pressure is set to 100 bar, while at stratified charge pressure varies between 150 and 200 bar, depending on rotational speed. If a fault occurs in the fuel pressure regulation system, fuel can be injected under low pressure of 5 bar.

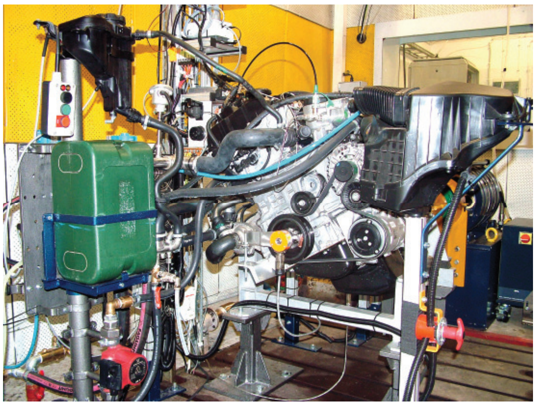

Fig. 2. Test engine N43B20 AY on the test stand

The test engine was mounted on the test stand (Fig. 2) equipped with AVL Zöllner eddy-current dynamometer type Alpha 240. Cylinder-out exhaust gas composition was measured with FTIR (Fourier Transform Infrared) multi-compound gas analytical system. In-cylinder pressure was measured with the use of miniature pressure transducer (AVL GH 12 D located directly in the engine head) and charge amplifier. Pressure signal was recorded with the use of data acquisition system with constant crank angle resolution of 0.1 °CA.

Main parameters of the engine operation were obtained via OBD (On-Board Diagnostics) data transmission. For the data recording and visualization in-house developed software was used.

3. Experimental results

In the first stage of experiments fuel consumption at full load-speed map was analyzed. The research was conducted for two mixture preparation modes; stratified charge and homogeneous charge. In order to obtain homogeneous mixture in the whole range of engine speed and load, error in the engine control unit was forced. In this case stoichiometric air-fuel mixture was kept with the use of a narrow-band oxygen sensor feedback signal. Results of the experiments are presented in Fig. 3.

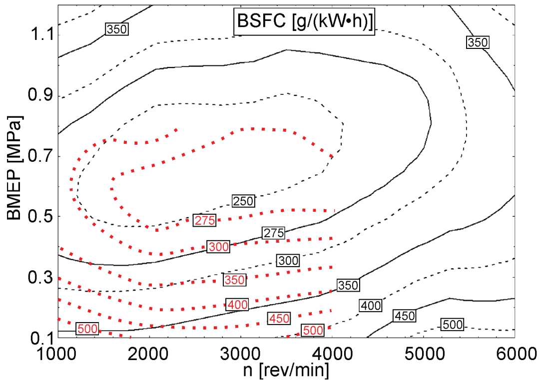

Fig. 3. Load-speed map of brake specific fuel consumption; dotted lines depict fuel consumption at homogeneous charge combustion

In the range, where stratified mixture is created in the combustion chamber, substantial reduction of fuel consumption versus homogeneous mixture is noticeable. Comparison of the fuel conversion efficiency for both modes of mixture formation shows that the biggest advantages are obtained at rotational speed between 1500 and 2000 rev/min and at engine load between 0,3 and 0,4 MPa of BMEP (Fig. 4). It should be noted that this is a range in which appears the highest density of operating conditions of such engine in NEDC test [9]. Overall air excess ratio is approximately 2 in this operation range.

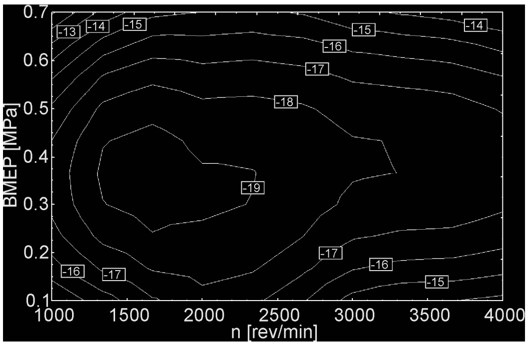

Fig. 4. Reduction (in %) of brake specific fuel consumption at engine operation in stratified mode versus homogeneous charge combustion

Combustion of the stratified charge created in the spray-guided combustion system is distinguished by higher heat release rate than in case of combustion of homogeneous mixture. Despite higher peak in-cylinder pressure values, maximum temperatures in combustion chamber are lower at stratified mixture operation. In this case maximum pressure occurs earlier and in-cylinder fluid mass is higher (doubled fresh air mass and high EGR rate). Figure 5 presents p-V diagrams at two modes of operation and constant rotational speed and IMEP. At stratified mixture operation air excess ratio (λ) was equal 2.1.

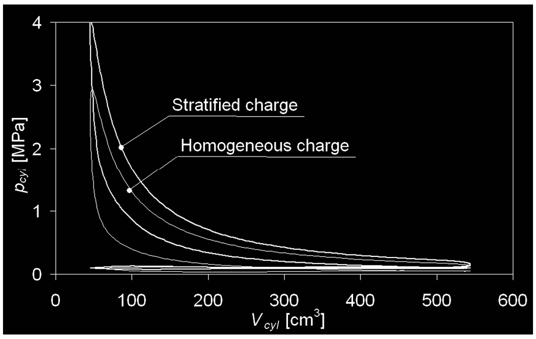

Fig. 5. Pressure – volume diagram at two modes of engine operation; n = 2500 rev/min, IMEP = 0,34 MPa

In both cases IMEP was equal 0.34 MPa, which resulted in the lower injected mass of fuel at the stratified operation. At homogeneous and stoichiometric charge combustion EGR valve was closed, while at creation of stratified mixture EGR valve was opened in 40%. At homogeneous charge relative pumping losses were about 17%, while at stratified operation these losses were approximately 7%.

Stratification of the in-cylinder mixture resulted in reduction of indicated specific fuel consumption (ISFC) from 263 g/(kW·h) to 219 g/(kW·h). It means increase of the thermal efficiency by 20%, half of which was obtained by reduction of pumping losses. Course of differential of indicated work in domain of crank angle is presented in Fig. 6.

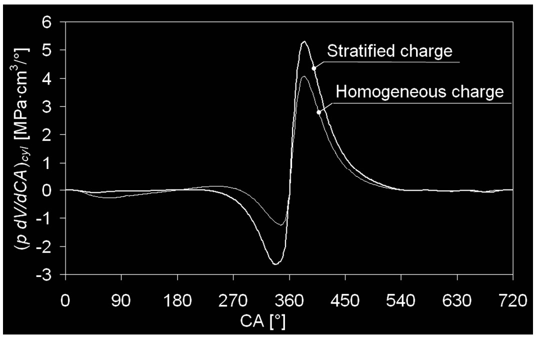

Fig. 6. Course of differential of indicated work versus crank angle for two modes of mixture formation; n = 2500 rev/min, IMEP = 0,34 MPa

Additionally, analysis of fuel consumption and emission of toxic exhaust compounds was done at variable air excess ratio. The engine was operated at constant rotational speed and torque. Indicated mean effective pressure was 0.34 MPa. Results of the research are presented in Fig. 7. In case of stoichiometric mixture homogeneous charge was created, while at leaner mixtures engine was run in the stratified mode.

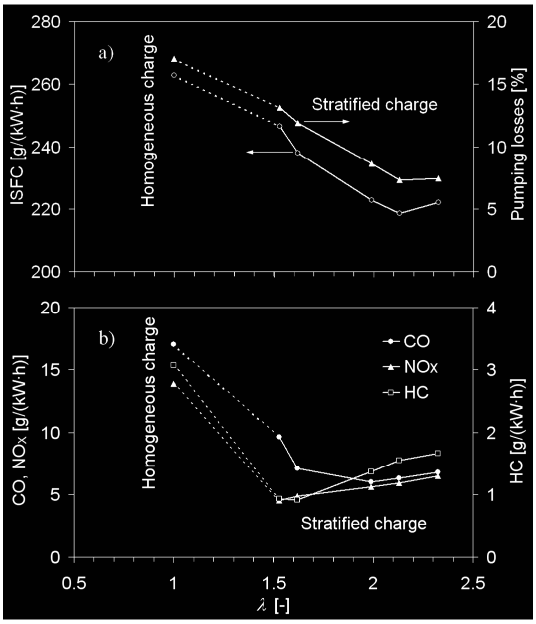

Fig. 7. Indicated specific fuel consumption (a) and indicated specific emission of exhaust toxic compounds (b) versus air excess ratio; n = 2500 rev/min, IMEP = 0.34 MPa

Indicated specific fuel consumption in some extent drops with increase of air excess ratio. Minimum ISFC was obtained at $\lambda = 2.1$. Further increase of air excess ratio results with negligible drop of thermal efficiency (Fig. 7 a). At normal operating temperature of the engine and factory settings of the engine management system at presented range of rotational speed and load air excess ratio is set to 2.1 (minimizing of fuel consumption).

Mixture stratification allows for reduction of emissions of all toxic compounds (Fig. 7 b). Minimum emissions of unburned hydrocarbons and NO_X occur at air excess ratio $\lambda = 1.5$. In comparison to combustion of homogeneous and stoichiometric mixture emissions of both compounds were reduced by 70%. However, further rise of air excess results with their increase. In relation to the minimum values, emission of unburned hydrocarbons rises by 80% at $\lambda = 2.3$, while emission of NO_X rises by 45%.

In case of unburned hydrocarbons the reason of emission rise with air excess is drop of the combustion temperature. As a result, flame quenching effect plays more important role in incomplete oxidation. It should be noted that, in general, unburned hydrocarbons content is relatively low. Mass of hydrocarbons in exhaust gas related to the mass of fuel does not exceed level of 0.4%.

Despite drop of temperature at leaner mixtures NO_X emission rises, mainly due to increase of oxygen excess in the reaction zone. It is also noticeable that molar fraction of NO_X in the range of stratified charge operation is almost constant and equals 740 ppm.

In general, combustion temperature and air excess ratio are two main factors which affect CO emission. At low temperatures conversion of CO into CO_2 at the end phase of combustion drops significantly. However, low amount of oxidizer at locally rich mixtures also results with increase of CO emission due to incomplete combustion. The relationship between temperature and air excess and its impact on CO emission is clearly visible (Fig. 7 b). Minimum emission was obtained at $\lambda = 2$ and increased both for leaner and richer mixtures.

4. Conclusions

In this study analysis of fuel consumption and toxic exhaust compounds emissions was done in the direct injection spark ignition engine. The engine was equipped with the spray-guided mixture formation system.

Combustion of the stratified charge at medium speed and load conditions allowed for increase of thermal efficiency by 20% versus homogeneous charge. Reduction of cylinder-out emission of all main exhaust toxic components was also noticed.

At factory settings of the engine management system and normal operating temperature the overall air excess ratio is set to minimize fuel consumption. At such air excess ratio emissions of unburned hydrocarbons and nitrogen oxides are higher than the lowest values, achievable at richer mixtures.

Nomenclature

BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific fuel consumption
CA	Crankshaft angle
cyl	Cylinder
DISI	Direct Injection Spark Ignition
EGR	Exhaust Gas Recirculation
FTIR	Fourier Transform Infrared
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specific Fuel Consumption
λ	Air excess ratio
n	Rotational speed
NEDC	New European Driving Cycle
p	Pressure
V	Volume

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