CHOSEN PROBLEMS OF COMBUSTION PROCESSES OF ADVANCED COMBUSTION ENGINE

Antoni Jankowski

Air Force Institute of Technology
Ksiecia Boleslawa Street 6, 01-494 Warsaw, Poland
tel.: +48 22 6851111, fax: +48 22 8364471
e-mail: antoni.jankowski@itwl.pl

Abstract

The latest intensive researches are directed on advanced low-temperature combustion (LTC), homogeneous charge compression ignition (HCCI), pre-mixed charge compression ignition (PCCI), reactivity controlled compression ignition (RCCI) and lean-burn petrol are presented in the paper. Engines with the direct injection of petrol (GDI) and Common Rail are subject of the paper. Engines the Scuderi and Holubowicz are described. The schema of Scuderi of engine is introduced. The original model of the combustion process is presented. Combustion rate at occurring of convection, velocity components of gases of liquid fuels changes combustion processes of these fuels. Increasing of velocity of the gas stream always increases the combustion rate, whereat the character of the influence is relative to the kind of the flow, which can be laminar, transient or turbulent. For the purpose of the comparison of experimental findings, one carried out calculations with the use of the modelling. In the modelling one used the ANSYS FLUENT programme which creates the opportunity of the modelling of the wide range of problems connected with the computational flow dynamics (CFD), both in reference to the flow of compressible fluids, as and incompressible, laminar and turbulent flows, phenomena of the transport, the heat exchange, with the occurrence and without the occurrence of chemical reactions. The field of the speed for the module from two velocity components introduced for the laminar and turbulent flow is presented.

***Keywords**: combustion engines, combustion processes, novel combustion engine design, CFD, model of combustion processes*

1. Introduction

The latest intensive researches are directed on advanced low-temperature combustion (LTC), homogeneous charge compression ignition (HCCI), pre-mixed charge compression ignition (PCCI), reactivity controlled compression ignition (RCCI) and lean-burn petrol. The target these researches are increase efficiency, reduce emissions level of nitrogen oxides (NO_x) and particulate matter (PM). Moreover, researches on emission control systems purpose to increase efficiency and durability for overall emissions compliance at an acceptable cost and with reduced dependence on precious metals. Research on engine efficiency including innovative combustion methods and thermal energy recovery e.g. compound cycles are realised, too [1, 2, 3].

Basic combustion processes will make possible the designing of engines with inherently lower emissions' level and advanced engines operating predominantly in low-temperature or HCCI combustion regimes. The resulting technological advances will reduce the size and complexity of emission control devices and minimize any impact these devices have on vehicle fuel efficiency. A fuel-neutral approach is being taken, with research addressing petrol-based LTC engines as well as diesel-based advanced engines. Increase overall engine efficiency through basic improvements such as advanced combustion processes, reduction of parasitic losses, and recovery of waste heat.
Improve the effectiveness, efficiency and durability of engine emission control devices to enable these engines to achieve significant penetration in the light-duty market and maintain their application in heavy-duty vehicles. Moreover, develop hydrogen engine technologies with near-zero NO_x, PM and greenhouse gas emissions. Develop advanced thermoelectric technologies for recovering engine waste heat and converting it to useful energy that will significantly increase vehicle fuel economy [5, 6, 7, 8, 9, 10, 11, 15].

2. Novel solutions of combustion engines

The idea of the increasing of the combustion rate in combustion engines is exceptionally essential, because permits to bring closer run working cycle of the engine to the theoretical cycle. The improvement of spraying of the fuel and the increasing of the turbulence of the load in combustion chamber raises this rate. Engines with the direct injection of petrol (GDI) and Common Rail are to this aim. Novel engines are the Scuderi and Holubowicz engines. In Scuderi the engine [12], working cycle is in 2 cylinders. In the first cylinder the suction stroke and compression is realized, in second – the working stroke and exhaust. Fig. 1 introduces the schema of Scuderi of engine. In the sucking engine compression pressure is about 50-65 bar, in supercharged – 110-130 bar.

Fig. 1. Scuderi engine (on the left compression cylinder) [12]

Good spraying of the fuel is as result of the airflow from one cylinder to second. The average temperature of the combustion is higher but is maximum lower. The diminution of the emission level NO_x and, the diminution of the level PM the emission to occur as a result the turbulence.

The engine Holubowicz [4] consists of two opposite cylinders in which connected two pistons realize the reciprocating movement, generate the electrical energy. The ignition and the combustion of the mixture in one cylinder causes reciprocation of the piston-group and compression of the load in the second cylinder. Exhaust gases does not influence directly on the cylinder.

3. Combustion systems

On Fig. 2, schema of SI engines realizing different systems of the preparation of the combustible (PFI and GDI) mixture represent. In PFI engines petrol is injected separately to intake channels of every cylinder. During the cold start, under transient conditions, in the area of surface of the intake valve is formed the film of the liquid fuel. The certain part of this steady state, oscillating film drags in to the cylinder during every admission stroke. The film of the fuel in the intake channel, the PFI engine works as the reservoir, whence the engine during the work receives specific amount of the fuel. During the start, it is necessary so to be injected the quantity of the fuel considerably exceeding required to retain on stable level of the stoichiometric ratio in the cylinder. In GDI systems, the fuel is injected direct to the cylinder of the engine.

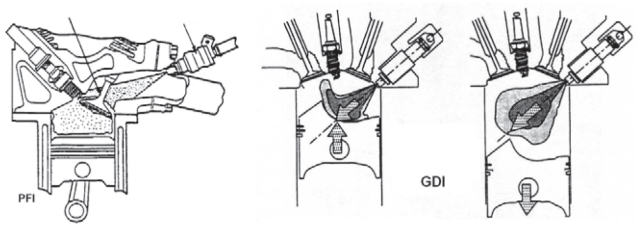

Fig. 2. Systems if the mixture preparation of the PFI and GDI engines [14]

GDI engines use two work systems map of rotational speeds (Fig. 3). This is the work at low loads and rotational speeds, at the strategy of the stratified load with the fuel injection in the late phase of the compression stroke and the work of within the range high loads and rotational speeds, when the strategy of the stoichiometric homogeneous load with the fuel injection in the earlier phase of the stroke of the filling is applied. It is necessary the introduction of the third strategy including the indirect range of loads and rotational speeds of the engine and to avoid instabilities in transition periods. In Fig. 3 the map of performance characteristics of the engine GDI in which are applied three strategies of the work of the engine: 1 – the stratified lean load; characterizes with the late injection in the compression stroke, with the high value of the coefficient of the excess of air (λ to 3), with the high EGR level what in effect makes for the small NO_x content, low-level fuel consumption and smooth (stable) work of the engine; 2 – the homogeneous stoichiometric load; it characterizes with the injection in the early stage of the stroke filling, with smaller requirements as against the octane number, with the good utilization of air and with the high volumetric efficiency , with high engine loads; 3 – the homogeneous lean load.

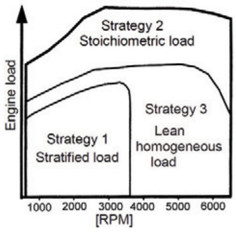

Fig. 3. The map of performance characteristic of the GDI engine [14]

Higher injection pressure is applied in the most of injection systems of the Common Rail type of GDI engines. GDI engines during the cold start have opportunities of the achievement low-level emission. Other still an advantage resulting from the use of the direct-injection is that the refrigeration of sucked in to the cylinder of air follows. In effect, the efficiency of filling increases. An important advantage of PFI engines to GDI engines is that the intake system works as the chamber of the preliminary vaporisation. In effect the level of spraying streams of the fuel must be enough large, so that it let on vaporisation of the fuel in this limited time. Injected direct to the cylinder the fuel in the GDI system should not impact crown of the piston and the cylinder wall. If GDI engines would have to equal to PFI engines, then would have to exceed it with properties which make advantages of PFI engines: the lower pressure of the work of the injection system, the ease of the utilization of toxic components thanks to the opportunities of the use of the three-functional (TWC) catalyst and higher temperatures of combustion gases what causes increasing of the working efficiency of catalysts. These properties make pointers for develop works on engines. Important limitations in uses of engines GDI are comparatively high level of the HC and NOx emission; whereat in these engines cannot be effectively used TWC catalysts. Working on extremely the lean mixture, the GDI engine will be characterized small NOx emission on the exit from the engine, but will not reach required through regulations of the emission level without the use of the catalyst. This level can be however obtained in PFI engines after the use of the TWC catalyst. Indeed one worked out many catalysts adapted to the work conditioned the lean mixture (so called *Lean NOx catalyst)*, but at present none provides of them the level of the conversion of TWC catalysts, on the wide range of the work of the engine and at the use of different fuels. An essential problem is also the excessive emission in low loads' conditions. Basing on well-known systems of the combustion and strategies of the steering, GDI engines one can classify in eight categories. First five categories is based on schemata of systems of the combustion, and remaining three refer to the applied system of the steering. Requirements concerning of the work of engines GDI in so various, constantly variable conditions place very high requirements with relation to parley of injection engines into which the course injection, ejection pressure, the speed of drops and the shape of the stream change together with the change-over of the engine.

4. **The model of the combustion process**

Combustion processes of liquid fuels are considerably more composed, than fuel gases. There is at this the various influence of external factors whose the interpretation is always very composed, like are submitted combustion processes. On the combustion rate decides process, which runs most slow down. In the situation of the combustion of homogeneous mixtures fuel - oxidant (air) this is kinetics of chemical reactions, however in case of heterogeneous mixtures – physical processes, the vaporization and the mixing.

One worked out the model of the combustion process of heterogeneous mixtures in which one accepted lower formulated assumptions:

there exists the interaction of the phase gaseous and liquid,

controlling processes the combustion are processes running most slow down,

in reference to liquid fuels process running most slowdown will be decomposition process of the liquid phase,

combustion processes of liquid fuels are relative to the boundary layer, which in turn is relative to the speed and the character of the flow of the stream of combustion gas, whereat this flow can be laminar, transient or turbulent,

the speed of the stream of gases intensifies combustion processes,

the speed and the kind of the stream of gases bears on the thickness of boundary layer,

the influence of the pressure on combustion processes of liquid fuels and gaseous is submitted, connected with the influence of the speed of the stream of gases and is relative to the kind of the fuel,

pressure increasing intensifies combustion processes in phase gaseous, but simultaneously decreasing the intensity decomposition of the liquid phase which controls the combustion,

the pressure increasing causes the diminution of the distance of the flame front from surface of the fuel, what increases the stream heat delivered to surface of the fuel and intensifies decomposition process of the fuel,

the intensification decomposition process of the fuel connected with the pressure increasing removes the flame front from surface of the fuel, whereat can appear three situations finally the opposed influence of the pressure and decomposition of the liquid phase:

if the flame front approaches to surface of the fuel, then with the pressure increasing follows the intensification of combustion processes,

if the flame front grows away from surface of the fuel, then with the pressure increasing follows rate reduction of the combustion,

if the flame front stays in the same distance from surface of the fuel, then one does not observe the influence of the pressure on the run of the combustion.

Most frequent is the first situation, so with the pressure increasing occurs the intensification of combustion processes, though not so essential as in reference to the combustion of fuel gases.

If in liquid phase, appear chemical reactions, then on these processes the pressure there is no influence.

A reflection of phenomena appearing in the combustion of liquid fuels is the boundary layer with perpendicular to surface an addition of the mass.

The most of previous models concerning of the combustion of liquid fuels (it establishes that the fuel is homogeneous, the combustion has the character established, the temperature on surface of the distribution of phases is a boiling heat of liquid. There one omits the influence of the radiation, the diffusion, changes of pressure, changes of physical characteristics and chemical of the fuel and the oxidant (airs, exhaust gas). One differentiates at these two situations: the combustion conditioned the lack of the convection (conditioned the micro gravitation) and conditioned occurrences of the convection, the earthly gravitation. This are so models very simplified which however give a certain view on processes running in ideal conditions.

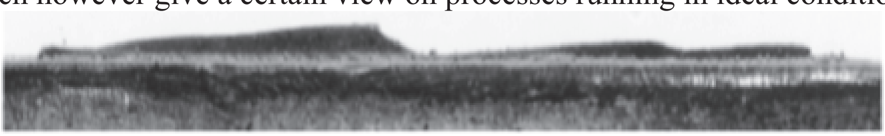

Fig. 5. Cross-section of burnt stripe of solid fuel

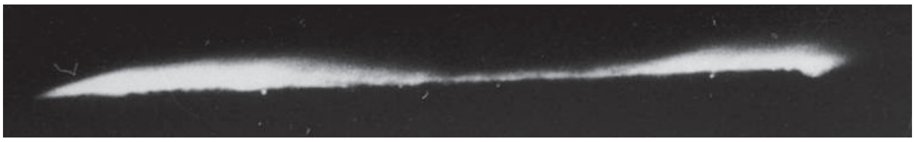

Fig.6. Cross-section of the boundary layer for burnt stripe

For the purpose of the comparison of experimental findings, one carried out calculations with the use of the modelling. In the modelling one used the ANSYS FLUENT programme which creates the opportunity of the modelling of the wide range of problems connected with the computational flow dynamics (CFD), both in reference to the flow of compressible fluids, as and incompressible, laminar and turbulent flows, phenomena of the transport, the heat exchange, with the occurrence and without the occurrence of chemical reactions etc.

The field of the speed for the module from two velocity components introduced for the laminar flow represented on Fig. 8.

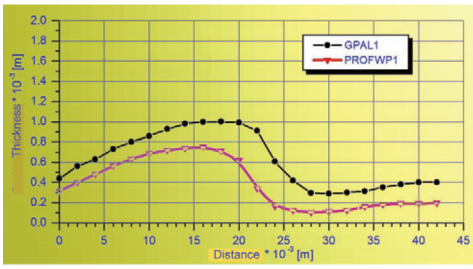

Fig. 7. The comparison of burnt of stripe cross-section and the boundary-layer

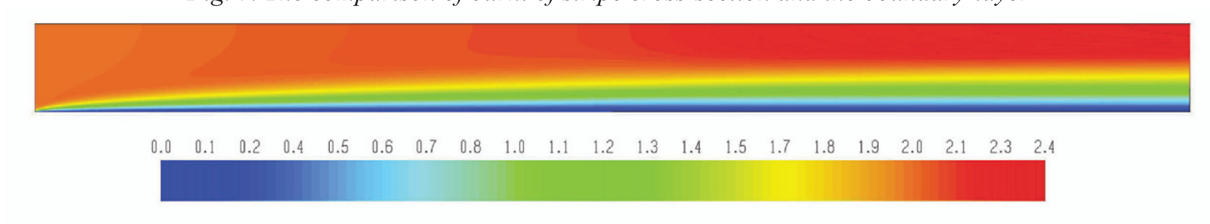

Fig. 8. The field of the speed (the module from two velocity components) for the laminar flow of Re = 236.6

The field of the speed for the module from two velocity components introduced for the flow turbulent represented on Fig. 9.

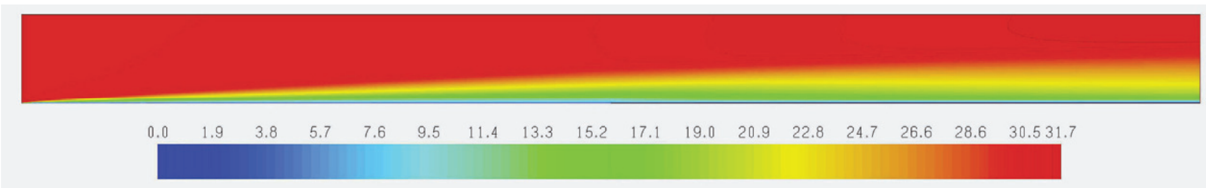

Fig. 9. The field of the speed (the module from two velocity components) for the turbulent flow of Re = 3 550

5. Conclusions

Combustion rate at occurring of convection, velocity components of gases of liquid fuels changes combustion processes of these fuels. Increasing of velocity of the gas stream always increases the combustion rate, whereat the character of the influence is relative to the kind of the flow, which can be laminar, transient or turbulent.

The pressure influences additionally on the velocity component of combustion rate, whereat this influence is different and depends mostly from the kind and the fuel parameters.
Fundamentally, pressure increasing increases the velocity component of combustion rate,
The pressure influences additionally on the speed component of the speed of the combustion, whereat this influence is different and depends mostly from the kind and characterizations of the fuel. However with reference to some fuels, with the pressure increasing, absence of the pressure

influence or even rate combustion reduction can occur.

The essential influence on the combustion process has a kind movement of combustion gases and the turbulence magnitude, and first of all the kind and thickness of the boundary layer. Generally, on combustion rate of liquid fuels, the essential influence has a kind (laminar, transient or turbulent) and the thickness of the thermal boundary layer around the fuel droplet. Performed photographs of the boundary layer confirm assumptions on the principle influence of the thickness and the kind of the boundary layer on combustion processes of liquid fuels.

References

[1] Chartier, C., Andersson, O., Johansson, B., Musculus, M. P. B., Bobba, M. K., *Effects of Post-Injection Strategies on Near-Injector Over-Lean Mixtures and Unburned Hydrocarbon Emission in a Heavy-Duty Optical Diesel Engine,* SAE Paper 2011-01-1383, 2011.

[2] De Ojeda, W., Zoldak, P., Espinosa, R., Kumar, R.: *Development of a Fuel Injection Strategy for Partially Premixed Compression Ignition Combustion,* SAE International Journal of Engines, Vol. 2, pp. 1473-1488, 2009.

[3] Hellstrom, E., Stefanopoulou, A., Vavra, J., Babajimopoulos, A., Assanis, D., Jiang, L., Yilmaz, H., *Understanding the dynamic evolution of cyclic variability at the operating limits of HCCI engines with negative valve overlap,* SAE Int. J. Engines, September 2012.

[4] Holubowicz, K. S., *Gun Engine,* http://www.gun-engine.info, 2010.

[5] Jankowski A., *Study of the Influence of Different Factors on Combustion Processes (Part Two)*, Journal of KONES 2009 Powertrain and Transport, Vol. 16 No. 3, pp. 135-140, Warszawa 2009.

[6] Jankowski A.: *Laser Research of Fuel Atomization and Combustion Processes in the Aspect of Exhaust Gases Emission,* Journal of KONES Powertrain and Transport, Vol. 15, No. 1, pp. 119-126, Warszawa 2008.

[7] Jankowski, A., *Heat Transfer in Combustion Chamber of Piston Engines,* Journal of KONES Powertrain and Transport, Vol. 17, No. 1 2010, pp. 187-197, 2010.

[8] Jankowski, A., *Study of the Influence of Different Factors on Combustion Processes (Part One)*, Journal of KONES 2009 Powertrain and Transport, Vol. 16 No. 1, pp. 209-216, Warszawa 2009.

[9] Jankowski, A., *The study of the influence pressure, rate and the kind of the gases' stream on the run of combustion process,* Scientific Works of Air Force Institute of Technology, Issue No. 28 Warsaw 2010 (in Polish).

[10] Parks, J., Prikhodko, V., Partridge, B., Choi, J. S., Norman, K., Chambon, P., Huff, S., *Lean Gasoline Engine Reductant Chemistry during Lean NOx Trap Regeneration,* SAE Paper 2010-01-2267, 2010.

[11] Powell, C. F., Kastengren, A. L., Liu, Z., Fezzaa. K., *The Effects of Diesel Injector Needle Motion on Spray Structure,* Journal of Engineering for Gas Turbines and Power 133, Issue 1, January 2011.

[12] Scuderi, S. C., Branyon, D. P., *Split Cycle Engine with Dell Piston Morion,* US Patent 6,986,329 2006.

[13] Sellnau, M., James Sinnamon, J., Hoyer, K., Husted, H., *Full-time Gasoline Direct-Injection Compression Ignition (GDCI) for High Efficiency and Low NOx and PM,* SAE 2012-01-0384, 2012.

[14] Tian, G., Wang, Z., Ge, Q., Wang, J. Shuai, S.: *Mode Switch of SI-HCCI Combustion on a GDI Engine,* SAE Paper 2007-01-0195, 2007.

[15] Yamaoka S., Kakuya H., Nakagawa S., Nogi T., Shimada A. Kihara Y.: *A Study of Controlling the Auto-Ignition and Combustion in a Gasoline HCCI Engine*, SAE Paper 2004-01-0942, 2004.