STUDY OF THE INFLUENCE OF DIFFERENT FACTORS ON COMBUSTION PROCESSES (PART ONE)

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Abstract

Combustion processes of liquid fuels are more complicated than gases fuels ones. With reference to liquid fuels appear additionally fuel vaporization processes and e.g. with reference to solid fuels - decomposition of the solid phase with processes melting, vaporization, pyrolysis, or gasification. Those processes demand a lot of heat, go ahead slow down than processes in gas phase. The influence of the gases pressure on combustion of liquid and solid fuels, where controlling processes are processes decomposition of these phases, is more complicated and fundamentally differs from the influence of the pressure on combustion processes of gases fuels. The influence is characterized to these that pressurization decreases the intensity decomposition both the liquid phase, and solid one. In the paper assumptions to a model of the combustion process and the model of combustion processes of liquid fuels are presented. Research of the atomization process, ignition and combustion with the using of the LDV and PDPA Doppler laser-equipment and PIV are presented in the paper. Research results of the atomized fuel spray concerning droplet diameters, research result of the atomized fuel spray concerning linear and volumetric dropletlet dispersion, Rosin-Rammler dependences, and results of the analysis of the combustion rate are presented in the paper. On combustion rate of liquid fuels, the essential influence has a kind (laminar, transient and turbulent) and the thickness of the thermal boundary layer around the fuel droplet.

Keywords: *combustion engines, combustion processes, fuel atomization, combustion modelling, laser research*

1. Introduction

Combustion processes of liquid fuels and are solid more complicated than fuel gases. With reference to liquid fuels appear additionally vaporization processes of the fuel, and with reference to solid fuels - decomposition of the solid phase with melting processes, vaporization, pyrolysis, or gasification. Vaporization processes, melting, pyrolysis and gasification demand a lot of the heat, run slowly down than processes in gas phase. It is necessary to underline that the influence of the pressure of gases on combustion processes of liquid and solid fuels, where controlling processes are processes of the decomposition of these phases, is more complicated and fundamentally differs from the influence of the pressure on combustion processes of fuel gases. The influence is characterized to these that pressure increasing decreases the intensity the decomposition both the liquid phase, as and solid one. For the purpose of the counteraction to such influence of the pressure, novel methods and manners for the purpose of the intensification the decomposition of these phases are searched. Among other things decreasing of sizes of dropletlets of the fuel by increasing of pressure and velocity of the atomized fuel spray, as well as turbulence stimulation of the stream of gases in the combustion engine belong to these methods. Obtain one can also the improvement of spraying of the fuel by the additional stream air using of directed to the atomized fuel spray, as well as additional mechanical atomizing using walls of combustion chambers with turbulence stimulation of the stream of gases. One can also use special devices which realize the process atomizing of the fuel in the way of the influence fixed walls and become independent of the fuel injection process from location in the combustion engine.

Velocity of the stream of gases and its kind which is laminar, temporary or turbulent, have an essential influence on combustion processes of liquid and solid fuels, whereat always appears the influence of the pressure which forces movement of the gases stream. The simultaneous influence of the pressure, velocity and the kind of the gases stream on run combustion processes is an object of research of many authors. This contemporary and also different influence is sometimes a reason of the misinterpretation of experimental results. Theoretical model the combustion process referring to liquid fuels was worked out. The model takes into account also the gas-phase, because chemical reactions take place in this phase, and besides the interaction of the gas-phase and liquid or solid ones appears. Theoretical model is presented basing on experimental Initial researches realized under conditions of model with reference to liquid fuels. Researches were realized in the constant volume chamber with measurements of pressure during combustion process with the use high-speed photography and with measurement of velocity distribution in the stream of the fuel and sizes of dropletlets with LDV and PDPA Doppler laser-equipment. This let on exact velocity measurement of combustion rate in the function velocity and the kind of the gases stream in the constant volume chamber, at registration burning zone by means of high-speed photography. In these research, what is very important, the influence of changes of pressure remained minimalized which always deforms picture of investigated phenomenon in the constant volume chamber or in the combustion engine. Initial researches of the boundary-layer by means of LDV Doppler laser-equipment let on measurement distribution in this layer at the simultaneous mass addition, what reflects processes of the decomposition both liquid fuels and solid ones.

2. Combustion model assumptions

Assumptions of the theoretical model are following referring to generalised processes of the combustion are following:

- the interaction of the phase gas- and liquid or solid ones exists , with this that both influences from the point of view of the mechanism of the process are such same,
- controlling processes of combustion processes are the processes running most slow down,
- with reference to liquid and solid fuels processes running most slow down will be processes of the decomposition of these phases,
- under the notion the decomposition, vaporization of the liquid phase and the melting and vaporization or pyrolysis, or gasification of the solid phase is described,
- combustion processes of liquid and solid fuels are relative to the boundary-layer which next is relative to velocity and the kind of the stream flow of combustion gases (laminar, temporary, turbulent),
- velocity of the stream of gases intensifies combustion processes,
- velocity and the kind of the gases stream influences on the thickness of the boundary-layer,
- the influence of the pressure on combustion processes of liquid and gas-fuels is complex, connected with the influence velocity of the gases stream and it depends also of the kind of the fuel,
- pressure increasing intensifies combustion processes in gas phase, but simultaneously makes difficult processes the decomposition of liquid and solid phase which controls combustion processes with reference to these fuels,
- next pressure increasing causes decreasing of the distance of flame front from the liquid fuel surface, what increases the heat flux to surface of the liquid fuel and intensifies decomposition of the liquid or solid fuel,
- intensification of the decomposition process of the fuel, connected with the pressure increasing, increases distance of flame front from surface of the liquid fuel, whereat can appear three cases,
- if finally the opposed influence of the pressure and the decomposition of liquid phase, the flame front of the draws on surface of the liquid fuel, then with the increasing of the pressure follows the intensification of combustion processes ,

- if finally the opposed influence of the pressure and the decomposition of the liquid or solid phase, the flame front of the goes off to liquid fuel surface, then with the pressure increasing follows the combustion rate,
- if as a result of the opposed influence of the pressure and the decomposition of the liquid or solid phase, flame front stays in the same distance from surface of the liquid fuel,
- this influence of the pressure on run of combustion processes does not appear,
- most often the first situation appears , so with the increasing of the pressure appears the intensification combustion processes, but not so essential as in the case of the combustion of gas fuels,
- if there are chemical reactions in liquid or solid phase, this pressure has not the influence on these reactions ,
- an image phenomena appearing in combustion of liquid or solid fuels is the boundary-layer with perpendiculars to surface of the separation of phases with mass addition.

The problems refers mostly to combustion processes with reference to the situation which appear during burns of the soot in converters of catalytic compression-ignition engines and generators of gases in air-cushions and launchers of arm-chairs of planes, so matters connected both with the issue pollutions, as well as with the safety of the exploitation of car vehicles and planes.

The problem refers also to combustion processes in compression-ignition engines with the direct-injection, in this with the "common rail" injection system and to engines with the spark-ignition with the direct-injection and is connected with the issue automotive pollutions. Preliminary investigations were effected basing on original methods of research permitting on exact measurement combustion rate by means of high-speed photography and measurement velocity distribution by means of LDV and PDPA Doppler laser-analysers. Researches were performed in the constant volume chamber with using of the original device for obtaining of the fine atomization of the fuel stream by means of the mechanical influence on injected spray, what make possible to obtain the fine atomization at low injection pressure. This permits also to obtain the combustion of liquid fuels in the constant volume chamber without its heating, what was not till now possible without the use of the original device for the fuel atomization. Theoretical model of heterogeneous combustion processes with take into consideration of two phases is presented on Fig. 1.

3. The model processes of the of liquid fuels

The most current models concerning the combustion of liquid fuels (solid) assumes that the fuel is homogeneous, the combustion has steady-state character, the temperature on surface of the separation phase is boiling temperature of the liquid. Models eliminate influence of radiation, diffusion, changes of pressure, changes of parameters physical and chemical of the fuel, air and exhaust gases. Two situations are taken into account: combustions under conditions absence of the convection (under conditions of microgravitation) and under conditions of the occurrence of the convection, the earthly gravitation. These models are very simplified, however give certain view on processes running under conditions of ideal. Equation of heat balance for the single droplet under conditions of described is dependence:

$$r^2 \frac{d}{dr}\left(\lambda \frac{dT}{dr}\right) + 2r\,\lambda \frac{dT}{dr} - \frac{\dot{m}\, h_s}{4\pi}\frac{d\left(c_{pg}T\right)}{dr} = 0, \tag{1}$$

where:

r – linear rate of the surface displacement of the separation of phases,

λ – coefficient of thermal conductivity,

T – temperature,

$\dot{m}$ – mass-rate of stream of liquid phase decomposition,

h_s – decomposition heat of liquid phase,
c_{pg} – specific heat capacity at constant pressure.

At assumption constant value of the λ and c_{pg} the dependence on the temperature distribution in gas phase of the combustion zone has a form:

$$\frac{T_f - T}{T_f - T_W} = \frac{exp\left(-\frac{\dot{m}\, c_{pg}}{4\,\pi\,\lambda\, r_0}\frac{r_s}{r_f}\right) - exp\left(-\frac{\dot{m}\, c_{pg}}{4\,\pi\,\lambda\, r_0}\frac{r_s}{r}\right)}{exp\left(-\frac{\dot{m}\, c_{pg}}{4\,\pi\,\lambda\, r_0}\frac{r_s}{r_f}\right) - exp\left(-\frac{\dot{m}\, c_{pg}}{4\,\pi\,\lambda\, r_0}\right)}, \tag{2}$$

where:
T_f – temperature of front flame,
T_w – temperature of surface of phases separation,
r_s – radius of fuel droplet,
r_0 – linear velocity of displacement of surface of phases separation in convection absent
r_f – radius of burn zone in convection absent.

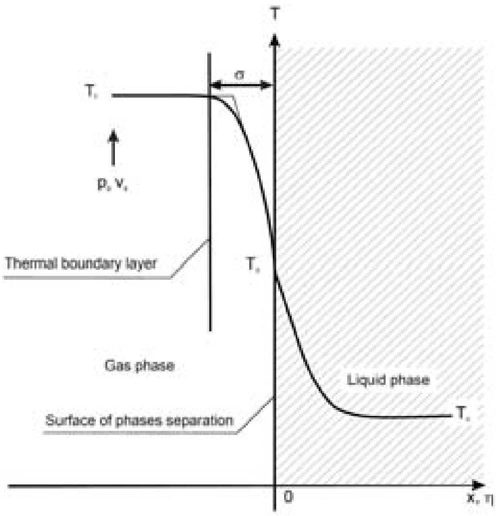

Fig.1. Theoretical model of heterogeneous combustion processes with the regard of two phases

At assumption that in the liquid phase appear no chemical reactions the balance of energy is described by the equalization:

$$\dot{m}\, h_s = 4\,\pi\,\lambda\, r_s \left(\frac{dT}{dr}\right)_{r=r_s}, \tag{3}$$

The mass-rate of the droplet combustion, which is received after solution of (2) and (3) equations, is described by equation:

$$\dot{m} = \frac{4\pi\, r_w \lambda}{c_{pg}\left(r_f - r_w\right)} ln\left[1 + \frac{\lambda_w\, c_{pg}}{\lambda\, h_s}\left(T_f - T_w\right)\right]. \tag{4}$$

where:

T_w – temperature of surface of phases separation,

λ_w – coefficient of thermal conductivity.

On the other hand, the mass-rate of the combustion is connected with size of droplet, what describes the dependence:

$$\dot{m} = -4\,\pi\, r_w^2\; \rho_w \frac{dr_w}{dt}\,, \tag{5}$$

where:

r_w – droplet radius,
ρ_w – droplet density on surface of phase separation,
t – time.

At additional assumptions, consisting in assumption that ratio flame radius to droplet radius ratio is firmed and after the introduction the droplet diameter instead of droplet radius of the fuel, and at assumption that the mass-rate of the combustion is proportional to the current droplet diameter , the following dependence describes change of the droplet diameter of the during combustion process:

$$d^2 = d_0^2 - k\,t\,, \tag{6}$$

where:

d – droplet diameter,
d_0 – initial droplet diameter,
k – constant rate of droplet combustion.

The dependence (6) is generally applied till now a dependence to define rate of combustion of the fuel droplet. It is proper to underline that constant rate of droplet combustion, *k,* is contained in narrow partition and its approximate value at droplet combustion in air is approx. 10^{-6} m^2/s. Mathematical model considers processes occurring in liquid and gas phase, particularly heterogeneous, particularly heterogeneous processes decomposition individual phase components, as and processes occurring in gas phase which affect processes decomposition of the liquid phase. These processes refer to real conditions , when combustion appears in combustion chamber, at the fuel injection to the combustion chamber, when appears intensive relative to gases movement of dropletlets . Droplets, because of heavy inertia with reference to gas stream, are not carried off by the gas stream, especially with reference to turbulent flow, large velocity differences of the gas stream and dropletlets occur. If decomposition rate of dropletlets from liquid to gas phase is less than combustion rate, flame quenching takes place. However both own observations , as and other authors show that the combustion rate can be indeed intensified at occurring turbulent stimulation of the gas stream in the combustion chamber.

Performed initial measurement of the thickness of the boundary-layer under model conditions, at using of the LDV laser Doppler equipment showed that the close relationship between the thickness of the boundary-layer and the combustion rate of liquid fuels as well as solid existed. So this theoretical model refers to heterogeneous fuels, both liquid and solid.

4. Research results

Researches of the processes of atomization, ignition and combustion at using of the LDV and PDPA the laser Doppler equipment, and PIV were performed. Research results of the stream fuel being composed of two kinds of principle small sizes of dropletlets within the range approx. 10 μ m and greater - within the range approx.50 μ m are shown on Fig. 2, 3 and 4.

Data for determine of the relative combustion rate in the constant volume chamber are shown on Fig. 5 and 6. These data show on differences of the combustion rate which are relative to the mixture ratio and atomization. Research results of the combustion process of the stream of the fuel, about proprieties presented on Fig. 2-4, introduces {represents} Fig. 7. Research results of the stream atomized fuel concerning diameters of dropletlets for small sizes of dropletlets - D32= 8.8 μ m, D43=11.1 μ m are shown on Fig. 8.

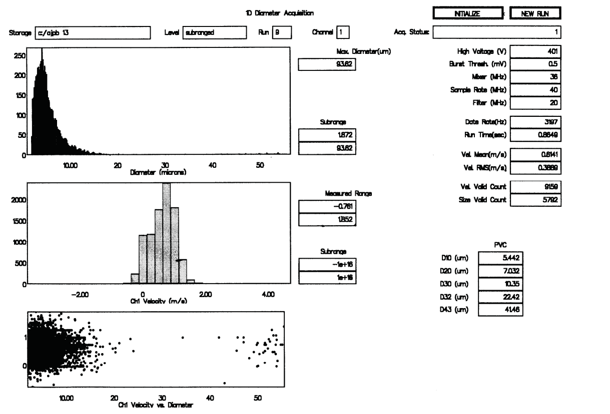

Fig. 2. Research results of the stream of sprayed fuel concerning diameters dropletlets for two kinds of principle of sizes of dropletlets, small within the range approx. 10 μm and greater - within the range approx. μm

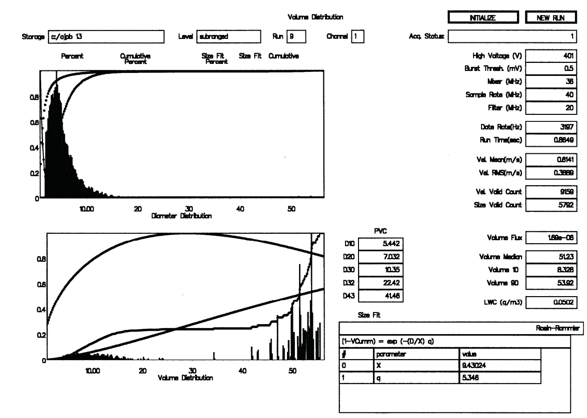

Fig. 3. Research results of the stream atomized fuel concerning distribution of dropletlets linear and volumetric and dependences Rosin-Rammler for two kinds of principle of sizes of dropletlets, small within the range approx. 10 μm and greater - within the range approx. 50 μm

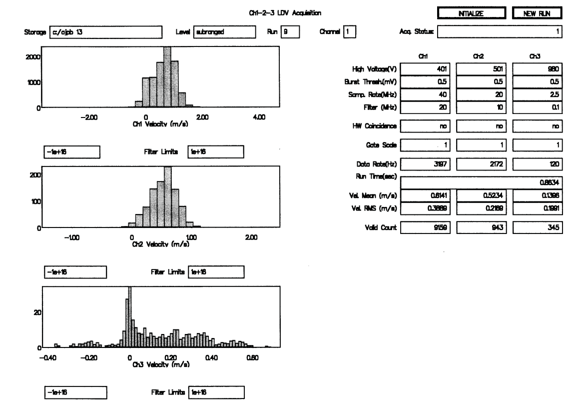

Fig. 4. Research results of the stream atomized fuel concerning 3D distribution velocity dropletlets for two kinds of principle sizes dropletlets, small within the range approx. 10 μm and greater - within the range approx. 50 μm

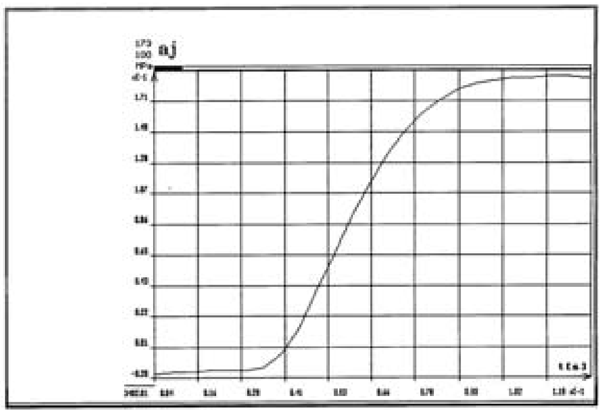

Fig. 5. The course the process of the combustion in the constant volume chamber for the stream of the fuel approx. D_{43} 28.8 μm, λ=2.8

5. Conclusions

On the ground performed preliminary investigations and on the ground worked out model following conclusions can be formulated:

- Combustion rate at occurring of convection, velocity components of gases of liquid fuels and solid 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.

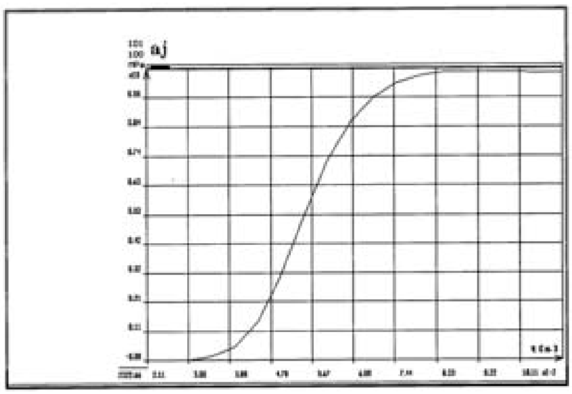

Fig. 6. The course combustion rate for fuel stream of the approx. D_{43} 24.23 μm, λ=1.8

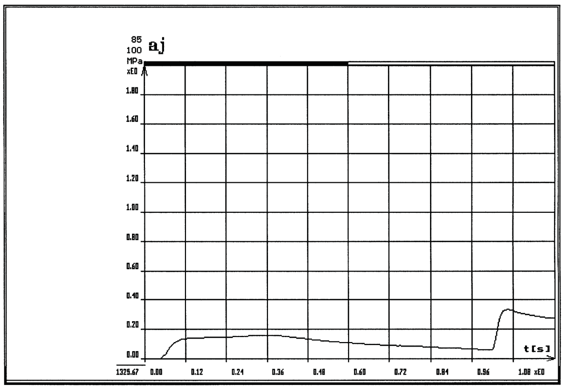

Fig. 7. The course of combustion process in the constant volume chamber for the stream of the fuel proprieties presented on Fig. 2 (λ=2.5)

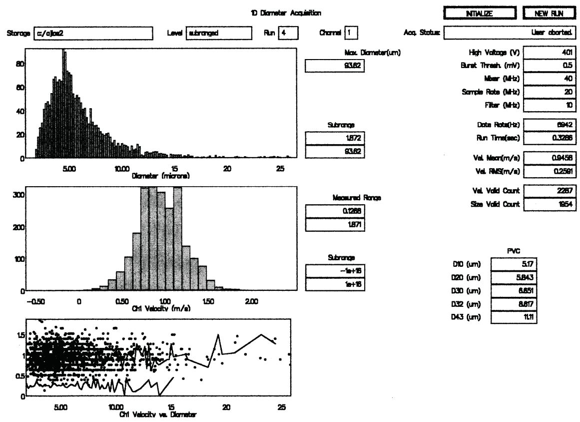

Fig. 8. Research results of the stream atomized fuel concerning diameters of dropletlets for small sizes of dropletlets - D_{32}=8.8 μm, D_{43}=11.1 μm

- 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.
- Conclusions referring to liquid fuels - fuel dropletlets can be put-upon to the analysis combustion processes of solid fuels, afterburning of small parts in catchers of small parts solid particulates for compression-ignition engines.
- 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 and solid fuels.

References

[1] Ambrozik, A., Jankowski, A., Kruczynski, S., Slezak, M., *Researches of CI Engine Fed with the Vegetable Fuel RME Oriented on Heat Release*, FISITA 2006, F2006P258 Paper, 2006.

[2] Buckmaster, J., Clavin, P., Linan, A., Matalon, M., Peters, N., Sivashinsky, G., Williams, F. A., *Combustion theory and modeling*, Proceedings of the Combustion Institute, Vol. 30, pp. 1-19, Pittsburgh 2005.

[3] Coltman, D., Turner, J. W. G., Curtis, R., Blake, D., Holland, B. Pearson, R. J. Arden, A., Nuglisch, H., *Project Sabre: A closed-Spaced Direct Injection 3-Cylinder Engine with Synergistic Technologies to achieve LowCO_2 Output*, SAE Paper 2008-01-0138, 2008.

[4] Corcione, E. F., Vaglieco B. M., Corcione, E. G., Lavorgna, M., Lanzafame, R., *Study of the combustion of a new small DI Diesel Engine with Advanced Common Rail Injection System*,

JSAE Paper/SAE Paper Int. Spring Fuels & Lubricants, Yokohama (Japan), SAE Paper 2003-01-1782, 2003.
[5] Guzzella, L., Onder, C. H., *Introduction to Modeling and Control of Internal Combustion Engine Systems, Springer*, Berlin Heidelberg New York, 2004.
[6] Heywood, J. B., *Internal Combustion Engine Fundamentals*, McGraw Hill International, 1988.
[7] Imaoka, R. T., Sirignano, W. A., *Vaporization and combustion in three-dimensional dropletlet arrays*, Proceedings of the Combustion Institute, Vol. 30, s. 1981–1989, Pittsburgh 2005.
[8] Ishihara, A., Sakai, Y., Konishi, K., Andoh, E., *Correlation between burning surface temperature and regression rate for polymethylmethacrylate*, Proceedings of the Combustion Institute, Vol. 30, pp. 2123–2130, Pittsburgh 2005.
[9] Itabashi, S., Niimi, K., Kamoshita, S., Oda, T., Shoji, A., Hirota, S., Watanabe, T., Study of Improvements in NOx Reduction Performance on Simultaneous Reduction System of PM and NOx, SAE Paper 2005-01-3884, 2005.
[10] Jankowski, A., Baczewski, K., Slezak, M., *Investigations of Influence of Aging Processes on Properties of Rapeseed Methyl Esters and Their Blends with Diesel Fuels,* FISITA 2008, F2008-09-059 Paper, 2008.
[11] Jankowski, A., *Influence of the pressure and the speed of the spray on processes of the combustion of solid fuels* (in Polish), IPOEX 2005, Jaszowiec 2005.
[12] Kim, E. S., Yang, V., *Modeling of Nitramine Propellant Combustion and Ignition, Energetic Materials: Initiation, Decomposition and Combustion,* Ed. P. Politzer, Theoretical and Computational Chemistry Series, Academic Press/Elsevier Science, New York 2003.
[13] Kruczynski. S. W., Danilczyk, W., Ambrozik, A., Jankowski, A., Slezak, M., *Performance of Three Way Catalytic Converter Containing Magnesium Oxide for SI Engines with Lean Mixtures*, FISITA 2006, F2006P237 Paper, 2006.
[14] Lamping, M., Kolbeck, A., Körfer, T., Adolph, D., Busch, H., Pischinger, S., *Advanced Diesel Combustion Method demonstrating favorable untreated engine emissions with improved consumption characteristics,* MTZ worldwide 01/2008, Volume 69, 2008
[15] Le Clercq P. C., Bellan J., *Modeling of multi component-fuel droplet-laden mixing layers having a multitude of species*, Proceedings of the Combustion Institute, Vol. 30, s. 2011-2019, Pittsburgh 2005.
[16] Lechner, G. A., Jacobs, T. J., Chryssakis, C. A., Assanis, D. N.,Siewert, R.M., *Evaluation of a Narrow Spray Cone Angle, Advanced Injection Timing Strategy to Achieve Partially Premixed Compression Ignition Combustion in a Diesel Engine*, SAE Paper 2005-01-0167, 2005.
[17] Matsumoto, Y., Gao, J., Namba, M., Nishida, K., *Mixture Formation and Combustion Processes of Multi-Hole Nozzle with Micro Orifices for D. I. Diesel Engines,* SAE Paper 2007-01-4050, 2007.
[18] Merola S. S., Vaglieco, B. M., Zarinchang, J., Simultaneous Detection of NOx and Particulate in Exhaust of a CR Diesel Engine by UVVisible Spectroscopy, SAE Paper 2003-01-0786 pP. 2020-2029, vol. 112 SAE Paper 2003 Trans Journal of Fuel, 2003.
[19] 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.
[20] Weber, J., Peters, N., Diwakar, R., Siewert, R. M., Lippert, A., *Simulation of the Low-Temperature Combustion in a Heavy Duty Diesel Engine,* SAE Paper 2007-01-0904, 2007.

The paper came into being as result of the realization scientific works within the framework of the research project No. 4 T12C 041 30 founded by Polish Ministry Science and Higher Education in years of 2006-2009.