AUTOMOTIVE SI ENGINE WITH INJECTION OF THE LIQUID LPG INTO THE INLET MANIFOLD

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Abstract

Non supercharged SI engine on LPG with mixture forming by evaporated LPG has lower power by about 8% compared to original petrol engine. This disadvantage can be eliminated by mixture forming by injection of liquid LPG. Report shows the results of the laboratory experimental research on an engine with injection of liquid LPG with the detailed analyses of the energy, power and emission engine parameters in 2 variations of the engine set-up. The thermodynamic analysis of the indicator diagram has shown that the characteristic parameters of the cycle (incl. parameters of the combustion course) stand practically identical for operation on petrol and on LPG. The measurements on the engine were also oriented on study of conditions in the inlet manifold after injection of the liquid LPG (injection visualization with fuel vaporization, temperature in the intake port) for an explanation of any abnormality on course of the unburned hydrocarbon concentration before catalyst. The experimental results show that automotive engine with injection of liquid LPG like high-quality variation of the car drive with favorable operating economy and positive ecological effects for environment.

Keywords: *gas fuel, mixture forming, power reducing, injection of liquid LPG, fuel vaporization, exhaust emission*

1. Introduction

Fuel system in most of present vehicle spark ignition (SI) engines is generally based on outer fuel/air mixture forming, which gives partially (petrol) or fully (gas fuel) prepared mixture for replacement of cylinder media on inlet to engine cylinder. Different properties of the fuels result in different energy contents of new fuel/air mixtures with petrol (BA) or LPG, resulting in a decline of engine power when engine is operating on LPG (gas fuel contains larger volume in mixture, thereby reducing the amount of air in the cylinder). The relative change of the value p_e in the condition of 100% load after the conversion of the petrol engine (λ=1) to the LPG is shown by the simplified relation (on the condition of the equal values of the filling efficiency and the overall efficiency of both the engines):

$$\frac{p_{e/LPG}}{p_{e/PF}} = \frac{\left(A_{T/PF} \cdot r_{air} + r_{PF}\right) \cdot H_{L/LPG} \cdot T_{BDC/PF}}{\left(A_{T/LPG} \cdot r_{air} + r_{LPG}\right) \cdot H_{L/PF} \cdot T_{BDC/LPG}}, \tag{1}$$

where:

p_e	- mean effective pressure of the engine working cycle,
$A_{T/PF} = 14{,}5$ kg/kg	- theoretical consumption of air for petrol fuel,
$A_{T/LPG} = 15{,}6$ kg/kg	- theoretical consumption of air for LPG,
$r_{air} = 287$ J/kg K	- individual constant of gas for air,
$r_{PF} = 76$ J/kg K	- individual constant of gas for evaporated of petrol fuel,

$r_{LPG} = 168$ J/kg K - individual constant of gas for evaporated of LPG,

$H_{L/PF} = 43{,}5$ MJ/kg - heating value (low) for petrol fuel,

$H_{L/LPG} = 46{,}1$ MJ/kg - heating value (low) for LPG,

$T_{BDC/LPG} \approx 350$ K - temperature of the cylinder charge at the BDC for evaporated LPG fuel.

$T_{BDC/PF} = 335$ K, - temperature of the cylinder charge at the BDC for evaporating petrol fuel.

The calculation employing the mentioned values gives the following result:

$$\frac{p_{e/LPG}}{p_{e/PF}} = 0{,}925\,. \tag{2}$$

The better solution in case of using LPG is multipoint injection of liquid LPG into the intake ports in the cylinder head or into the inlet manifold close to the cylinder head. Steaming LPG provides lower temperatures at the end of filling cylinder against running with petrol. Opposite previous case using this injection gets rise of specific filling fresh air in cylinder. Injection of liquid LPG decreases temperature of cylinder primer at the end of intake stroke on value $T_{BDC/LPG-inj} \approx 325$ K (heat of evaporation LPG in t = 20 ^{0}C is $L_{LPG} \cong 360$ kJ/kg): next relative change of rate p_e will be:

$$\frac{p_{e/LPG}}{p_{e/PF}} \cong 0{,}995\,. \tag{3}$$

The results shows that an engine with injection of liquid LPG has practically same power as the same engine running on petrol fuel (PF). Operation on liquid LPG poses, however, a risk of freezing of the injectors due to very fast evaporation injected LPG. It therefore demands special alterations on injectors and well-considered development incorporation of the injectors in the inlet manifold.

2. Results of measurement

The power and emission characteristics of vehicle SI engine with injection of liquid LPG were measured in the KVM laboratory at the FS TU in Liberec. Engine was equipped with a LPGi fuel system (Vialle, Netherlands); injectors with nozzles (MPI) were placed in the inlet manifold. The nozzles provided for gradual expansion and evaporation of the liquid LPG. Several variations of types of construction by the injectors were verified during the tests. All tested nozzles had practically identical properties in term of temperatures in the inlet manifold and exhaust emissions. Differences in geometrical dimensions by the individual types of the nozzles resulted, however, in differences in engine power: final measurements were realized with simple type of pipe nozzles (see fig.1).

The engine for metering was equipped with necessary sensors (microthermocouple in intake port – see fig.2, pressure sensor for high-pressure indication and incremental sensor for position of the crankshaft) and sampling of the exhaust gases before and after the catalyst. Engine power, states of temperature and pressure, specific fuel consumption and concentration of gaseous components in exhaust emissions were measured on the test bench. All measured values were recorded by an electronic data acquisition system at a rate of 5 second steps for record. The operation of engine on LPG was managed by engine control unit VIALLE connected with the original petrol ECU, which throughout the operation conditions set values of spark advance, time for injection of LPG, air/fuel ratio from programme for running in petrol mode.

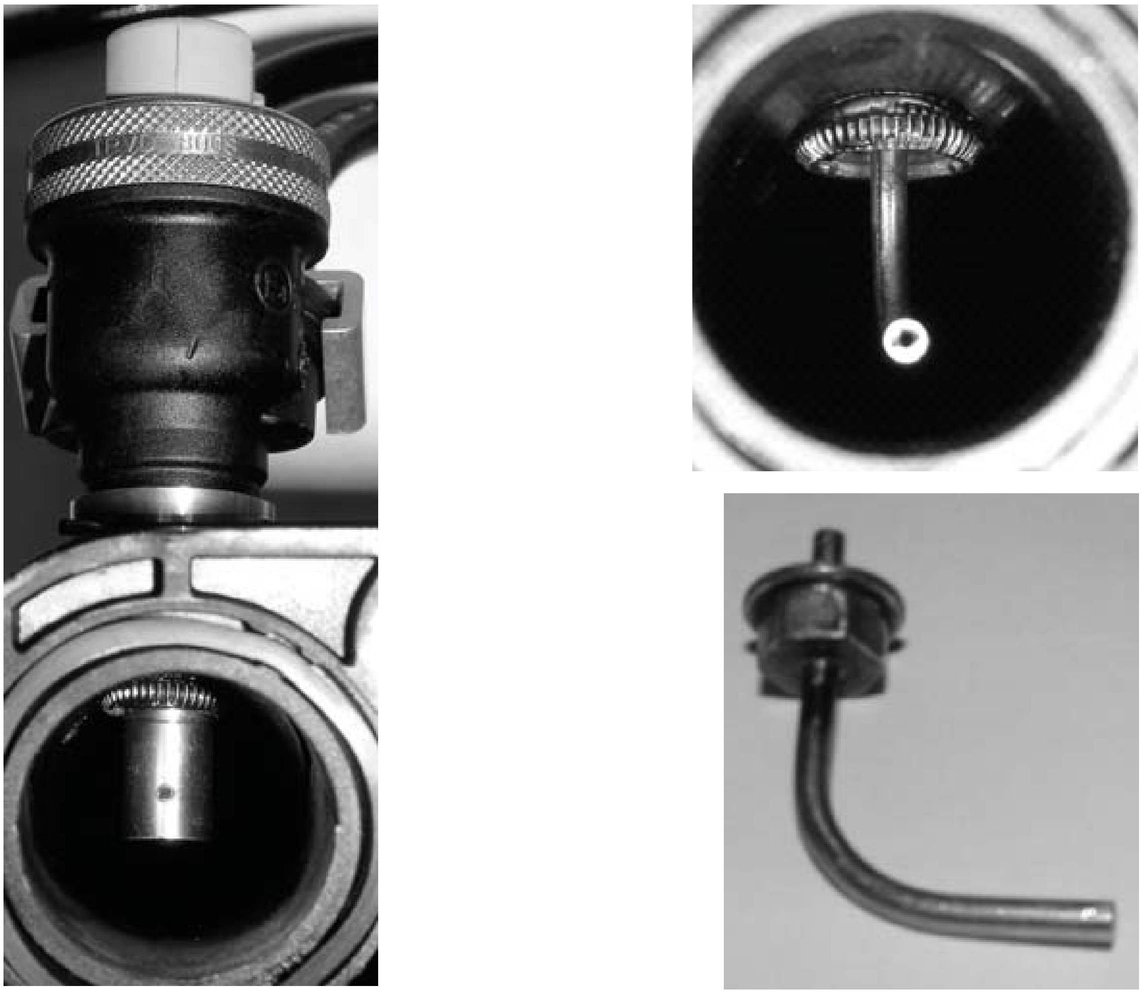

Fig. 1. The LPG injector placed on the inlet engine manifold and chambered nozzle in the inlet manifold (left), pipe's nozzle in the intake manifold and the view on the type of pipe's nozzle (right)

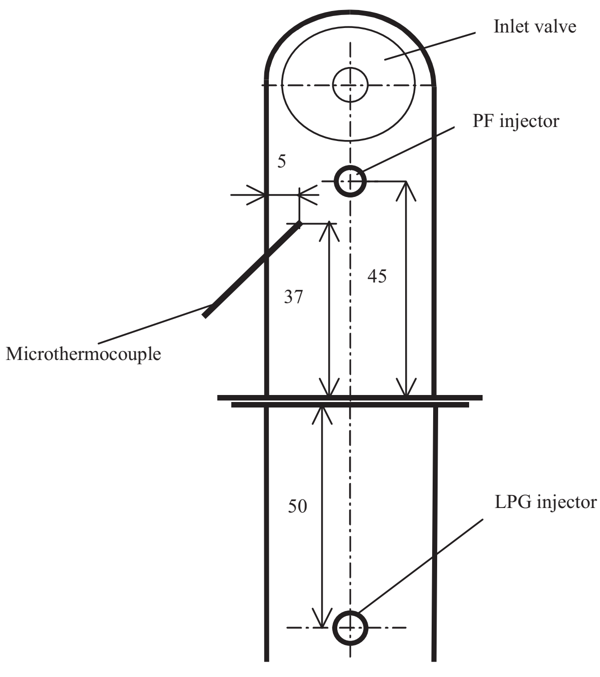

Fig. 2. The scheme of microthermocouple in the intake port in cylinder head for metering air (mixture) temperature before the intake valve. The scheme of dimension location for measuring temperature in the intake port of the engine (dimensions shown are reached at extended central axis of the port)

The test engine measurement was done with manual settings of the spark advance, injection of LPG and air/fuel ratio of mixture, in order to investigate the effects of all important operating engine parameters on settings different from the original ECU settings for operation on petrol. The results of metering showed that programmed spark advance and fuel injection maps in the original ECU for petrol running correspond very well for engine operation on LPG, except for the regulation of air/fuel ratio in conditions of high load which was optimized differently for each fuel.

The parameters of automotive SI engine used on LPG with injection of liquid LPG close to the end of intake manifold in face of intake ports in the cylinder head are shown in Fig.3 through Fig.12 and in Table T1.

Fig.3 shows the comparison of achievable values of effective mean pressure in the engine working cycle by the engine, which was alternately operated on petrol and on LPG with mixture forming either by force of converter (mixer) or multipoint injection of the gaseous fuel. The measured results confirm a decrease of engine power when using LPG, which is in line with calculated estimation from the equations (1) and (2). By forming mixture in converter the parameters of power decrease more markedly than calculation estimation due to needed reduction of wetted cross-section of converter diffuser. Decline of power by using multipoint injection of gaseous LPG is roughly half compared to forming mixture in converter. Values of p_e in full load conditions in the entire useful speed range by running on LPG were measured with stoichoimetric air/fuel ratio, while engine working on PF (petrol fuel) ran in full load conditions with a rich mixture ($\lambda \cong 0{,}9$) due to reduction of the temperatures of the exhaust gases (for catalyst protection). The loss of power on LPG resulted in lower exhaust gas temperatures, thereby allowing operation on stoichoimetric structure of mixture without the risk of catalyst damage.

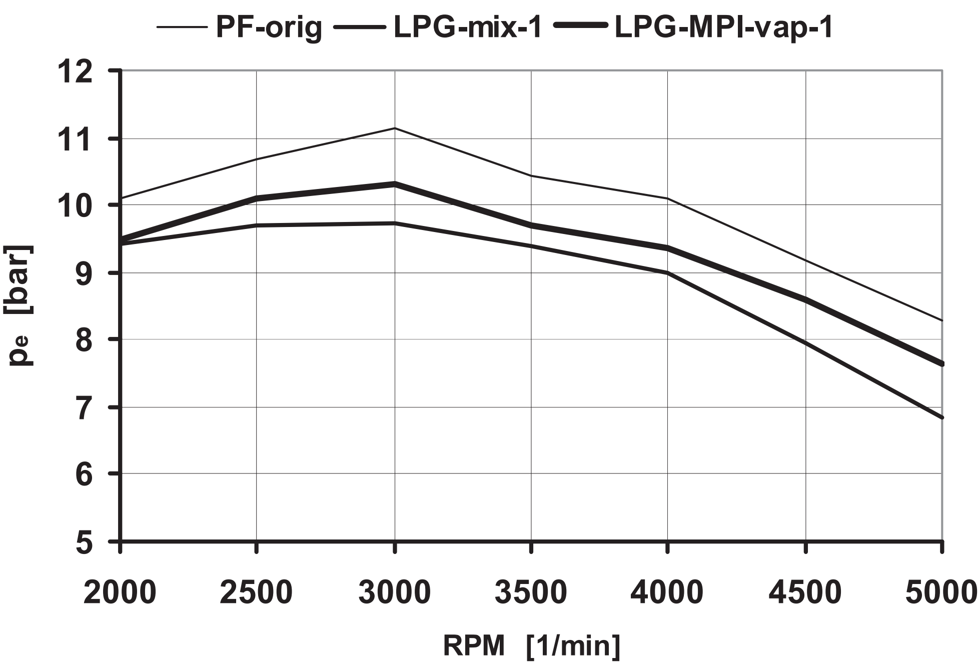

Fig. 3. Disposable values of the BMEP throughout the engine working cycle for full load at running on PF and on LPG (variant with the mixture forming by mixer and by multipoint injection of evaporated LPG)

Fig.4 shows a great influence of exhaust gas back-flow from engine cylinder into the intake port on the fresh mixture temperature (logically the greatest back-flow to the intake port is during conditions with low load). A notable effect of the vaporization of the injected LPG associated with the decline in the charge temperature leads to an increase in cylinder charge mass compared to the mixture forming by gaseous LPG, and exhibits only smaller decline of power engine parameters against running on PF.

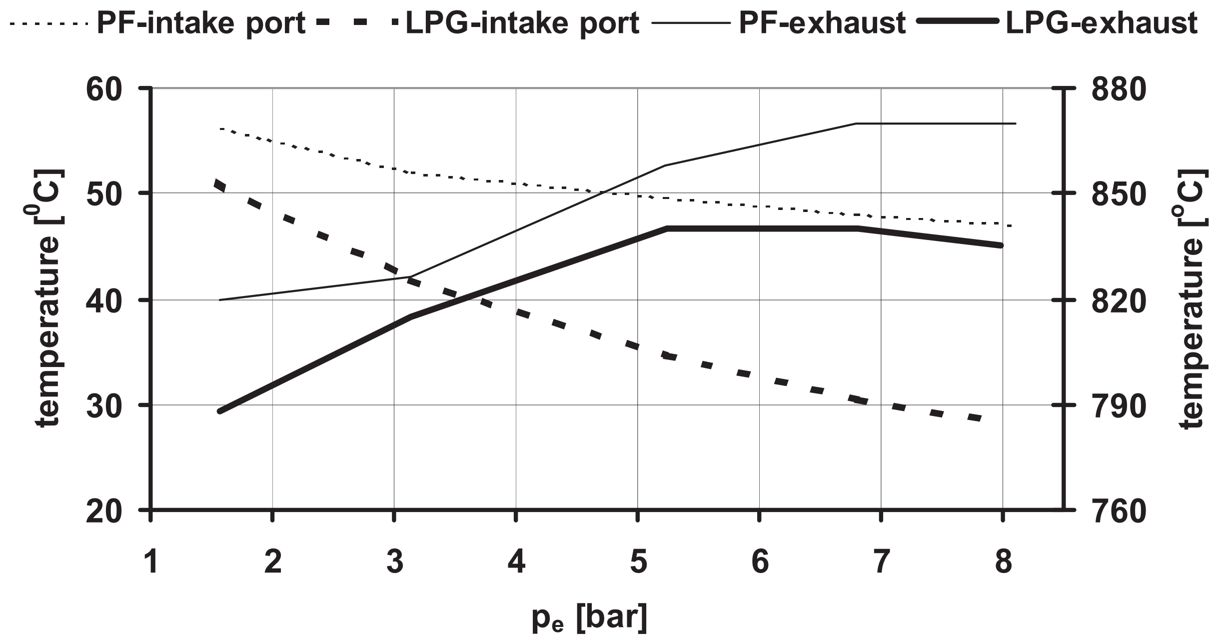

Fig. 4. Fresh mixture temperature in intake port at cylinder head and exhaust gas temperature at 5000 rpm (the temperature in the intake port is determined as arithmetic mean of 16-18 recorded temperatures for each measurement point, the exhaust gas temperature there is calculated as arithmetic mean from several points at the end of each measurement mode)

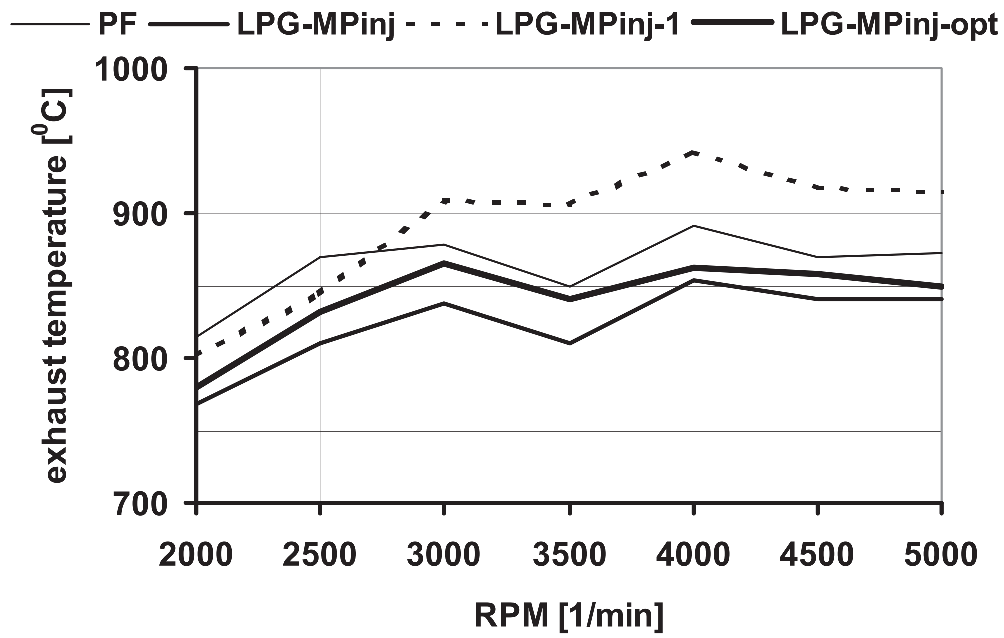

Fig. 5. The courses of exhaust gas temperature in full load conditions for experimental SI engine running on PF with original ECU for regulation of the mixtures richness and for running on LPG with different setting of the air/fuel ratio governing

The graphs on fig.5 show that engine working on LPG with mixture richness according to original programme in ECU (for PF) exhaust gas temperature are the lowest for the all RPM range. Engine running on LPG with mixture $\lambda = 1$ gives for all RPM range of all measured variants the highest exhaust gas temperatures. By an optimization of the air/fuel ratio control by an auxiliary ECU it is possible with running on LPG to achieve the meaningful decrease exhaust gas temperature compared to stoichiometric operation. .

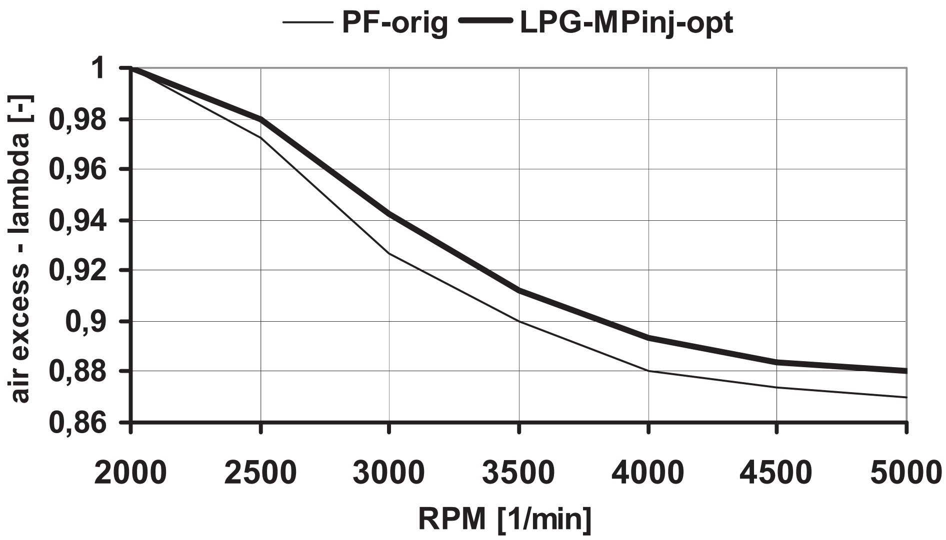

Fig. 6. The optimized governing of the mixture richness for full load conditions of the experimental SI engine with injection liquid of LPG to the intake manifold in face of intake port at cylinder head

By the engine running on LPG with the optimized air/fuel ratio control, engine power parameters were achieved which were virtually coincident with the parameters of the original motor running on PF. Exhaust gas temperatures at this setting are comparable to the exhaust gas temperatures on the original engine running on PF. The optimized course (see fig.6) of the mixture richness governing was realized by the special programmable ECU, interface to the original ECU of the engine.

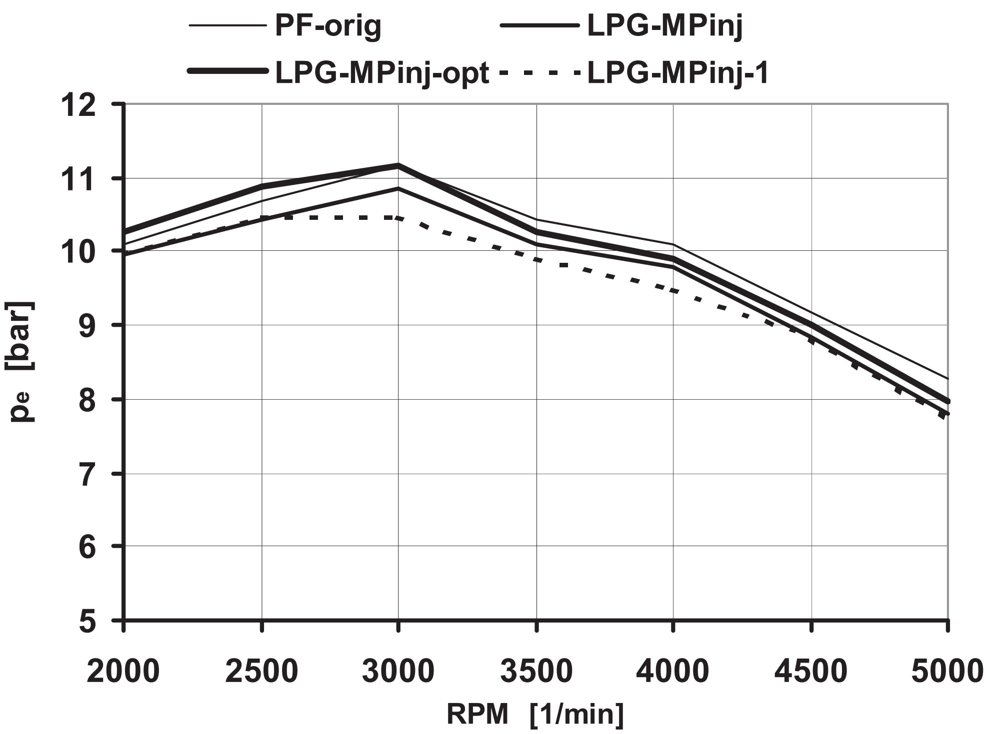

Fig. 7. Disposable values of the BMEP throughout the engine working cycle for full load conditions at running on PF and on LPG (variant with the mixture forming by multi-point injection liquid LPG with the different richness of the mixtures: on setting LPG-MPinj the mixture is enriched according to governing programme by ECU as well as for PF, the mode LPG-MPinj-1 is variant for stoichiometric mixture and setting LPG-MPinj-opt is mode mixture optimized governing in relation to limit value of exhaust gas temperature)

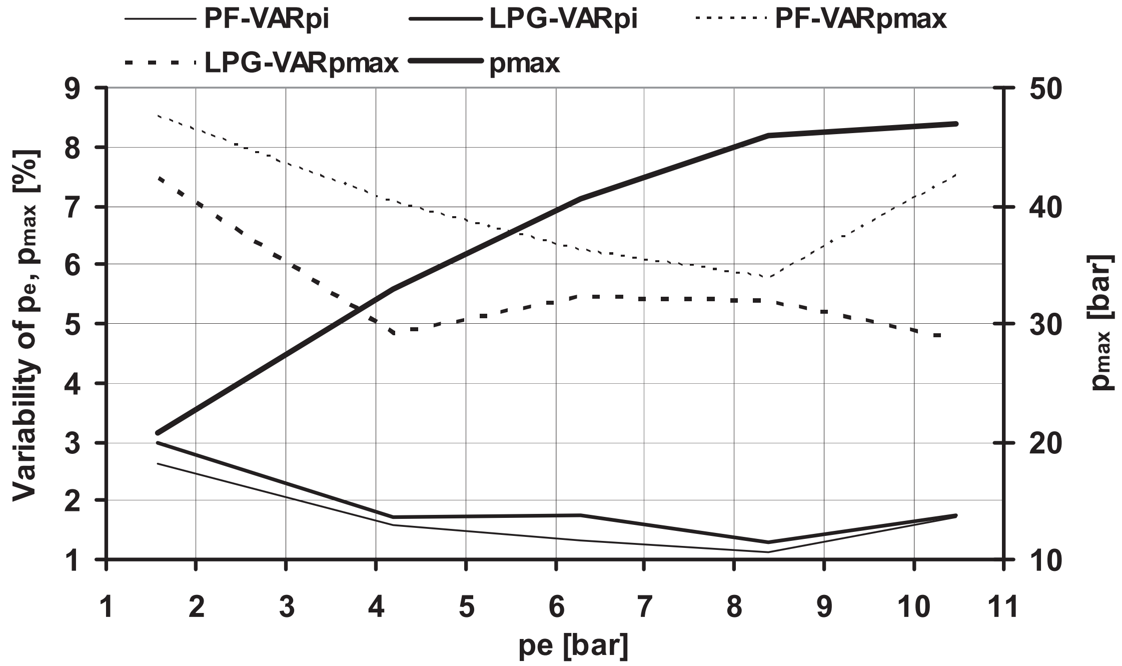

Fig. 8. Combustion peak pressures on load characteristic at RPM = 3000 1/min they have at engine running on PF and on LPG virtually like the same values, the parameters of the intercycles variability for PF and LPG they are for p_i as well comparable, the engine running on LPG has a somewhat lower values of intercycles variability for p_{max} (by using statistical processing of the set 150 sequential following cycles)

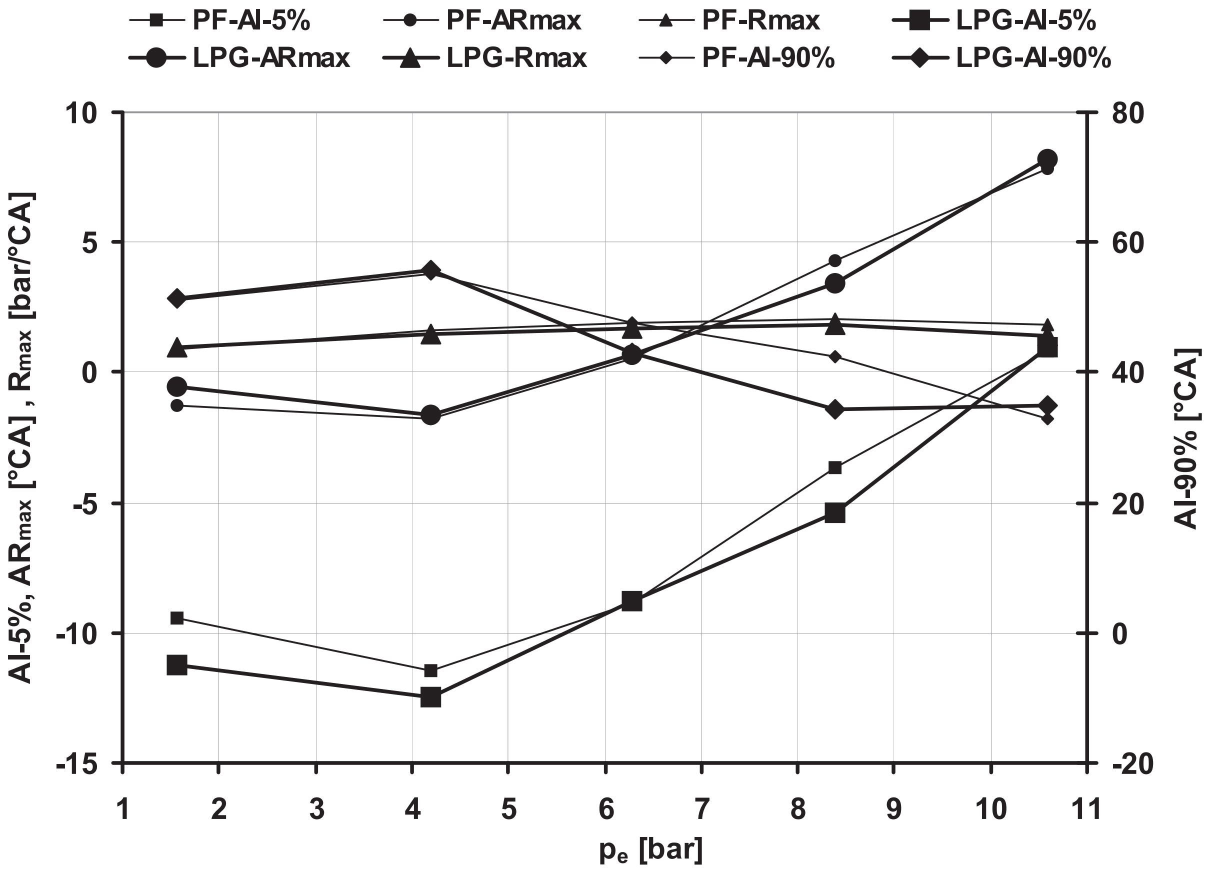

Fig. 9. The parameters of the course of mixture combustion at cylinder at running on PF and on LPG on load characteristic at RPM = 3000 1/min

From thermodynamic analyses set 150 measured indicator diagrams with the statistical processing of the combustion parameter values the following characteristics have been determined:

- The start of the combustion, defined as release of 5% heat from the total supply of heat to the working cycle (Al 5%), expressed as the angular position of the crankshaft in relation to TDC.
- The end of main combustion phase of mixture at cylinder, defined as release of 90% heat from total supply of heat to the working cycle (Al 90%): the end of main combustion phase of mixture at cylinder is identified by position of the crankshaft after TDC.
- The highest gradient R_{max} on course of the cylinder pressure (in p-α diagram), defined as the highest increment of pressure during any one degree of angular rotation of the crankshaft.
- The position AR_{MAX} of the biggest gradient R_{max} on the course of cylinder pressure, determination by angular position of the crankshaft in relation to TDC.

The values of the observed parameters on the pressure courses and burning at the cylinder, shown on the diagrams at Fig.8 and Fig.9, are practically identical for operation on PF and on LPG.

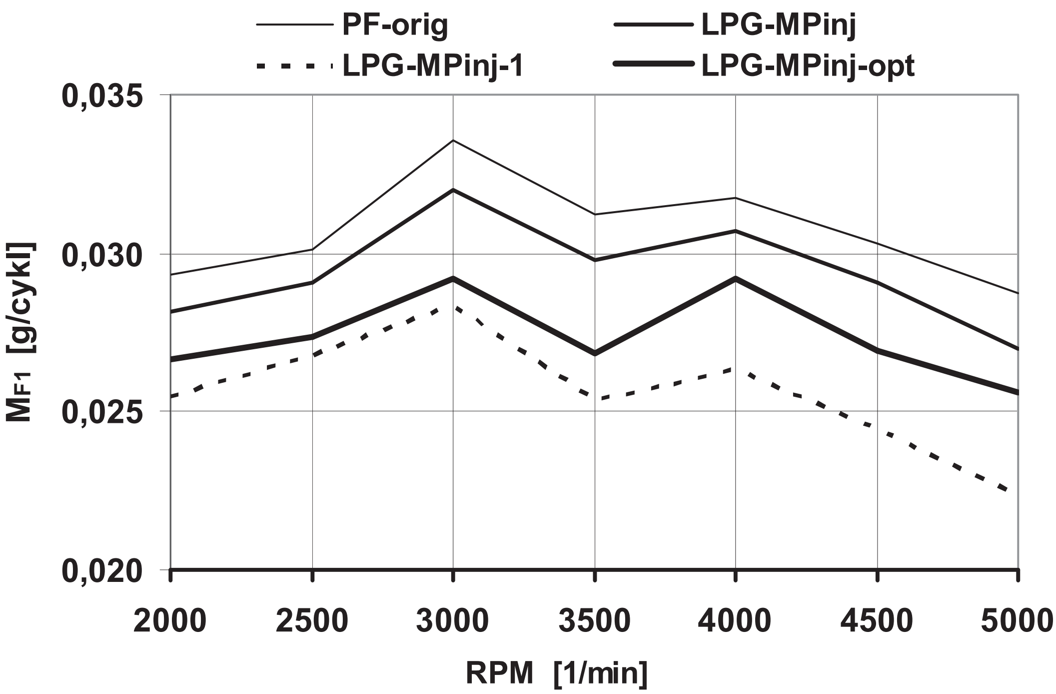

Fig. 10. The injected fuel quantities for full load conditions at running on PF and on LPG for different variants of the experimental engine they reflect the right functional coupling original ECU of PF engine on ECU Vialle fuel system for injection of the liquid LPG

The differences between courses (see fig.11) for setting PF-orig and LPG-MPinj-1, resp. LPG-MPinj-opt they logically reflect the important influence on the mixtures richness. The change of the mixture enriching for optimized variant LPG-MPinj-opt means the fuel consumption is reduced about 5-6% at full load conditions.

The mean THC concentrations at engine running on LPG are lower compared to concentrations at engine running on PF. It should be noted, however, that the THC concentrations fluctuated substantially during operation on LPG, reaching peak values several times higher than the mean value. The experimental engine on test bench (and in vehicles too) running on liquid LPG had random perturbances ("jerks"), which were noticed with all investigated types of injection nozzles, and which remain largely unexplained, with one hypothesis claiming freezing during fast vaporization of liquid LPG.

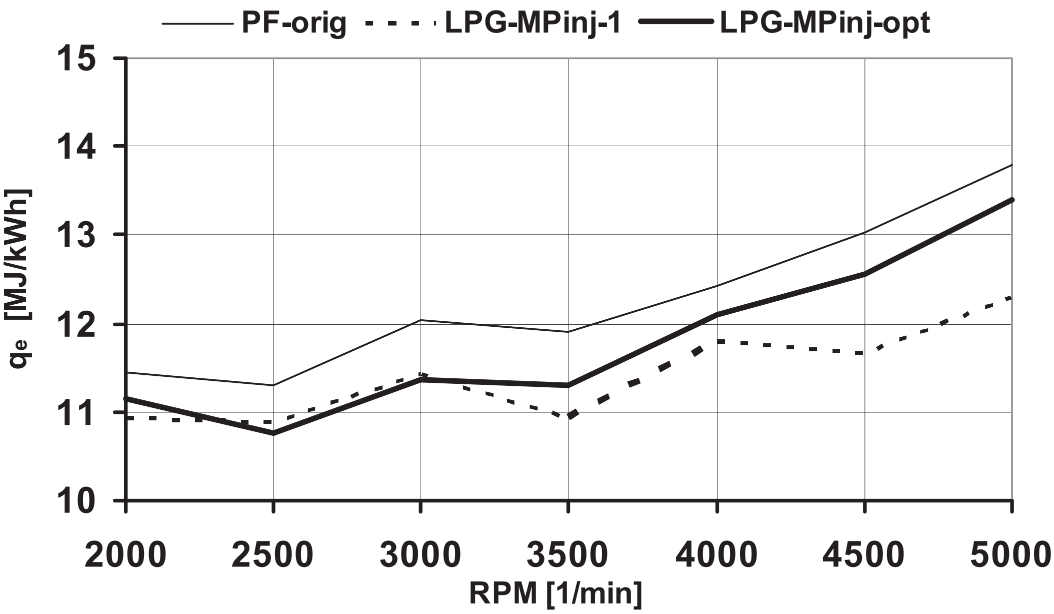

Fig. 11. Specific consumption of the heat on full load speed characteristic for different variants of experimental engine

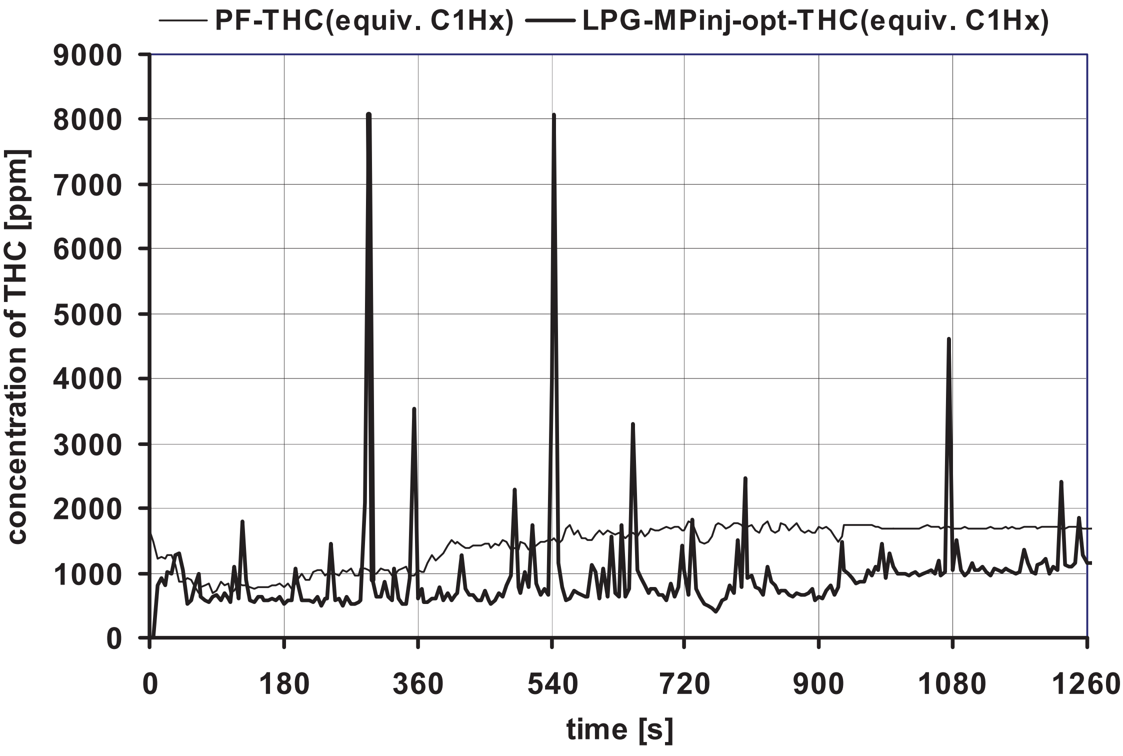

Fig.12. The course of the THC concentration from metering on experimental SI engine with injection of liquid LPG (fuel system VIALLE) at full load speed characteristic (with the electronic data acquisition from analyzer at 5s step) at comparison with the course of the THC concentration from metering on engine PF running

3. Conclusion

- Experimental vehicle SI engine with mixture forming by multi-point injection of the liquid LPG (fuel system Vialle, injection to the intake manifold in face of intake port at cylinder head) has the most optimal properties (power, emission, running and temperature) of all experimental engine version modified for running on LPG. For full utilization of the engine concept potential with mixture forming by injection of liquid LPG, it is need to minimize the reduction of the cross-section in the intake manifold resulting from the installation of injector nozzles in the intake manifold.

- The fuel system with injection of liquid LPG is, according to the manufacturer, insensitive on worse quality of LPG (LPG with increased content of heavy vaporizable components), which for systems based on mixing of evaporated LPG and air (mixer or gas injection) has can pose significant operational problems (the poor quality of LPG remains still big problem).
- The metering show high catalyst efficiency at stoichiometric mixture on both PF and LPG. At rich mixture (in high load for engine) the catalyst's efficiency on THC is lower at LPG compared to PF, the THC emission at running on LPG they are however comparable with THC emission while running on PF (at running on LPG the concentrations THC in exhaust gases on input to the catalyst are lower than running on PF that is why final emission of THC are comparable at running on LPG and PF). During operation at full load at various rpm, the emission of CO are somewhat higher by running on LPG against running on PF (by up to 1%), the NO_x emission remain comparable for both fuels (see table T1).

Tab.1. The measured values on the experimental SI engine by different variations and condition

Experimental SI engine on full loading										
	PF- orig		LPG-MPI-vap-1		PF with LPG injectors		LPG-MPinj-opt		LPG-MPinj-1	
	3000 min^{-1}	4750 min^{-1}	3000 min^{-1}	4750 min^{-1}	3000 min^{-1}	5000 min^{-1}	3000 min^{-1}	5000 Min^{-1}	3000 min^{-1}	5000 min^{-1}
p_e [bar]	11,20	8,38	10,16	7,75	10,84	7,85	11,07	7,91	10,58	7,85
CO_{BC} [%]	3,1	3,8	1,1	0,85	3,5	4,7	4,7	5,8	0,58	0,54
CO_{AC} [%]	3,0	3,7	0,42	0,36	3,8	4,8	4,6	5,6	0,16	0,07
THC_{BC} [ppm]	2120	1770	765	580	1990	1300	885	1035	600	800
THC_{AC} [ppm]	290	230	40	15	250	255	315	435	35	45
NOx_{BC} [ppm]	1780	1955	2980	3605	935	1270	740	1010	3080	3675
NOx_{AC} [ppm]	540	860	435	660	270	345	230	340	670	1310
$\eta_{CAT/CO}$ [%]	3	3	62	50	0	0	2	3	72	87
$\eta_{CAT/HC}$ [%]	86	87	95	97	87	80	65	58	94	94
$\eta_{CAT/Nox}$ [%]	70	56	86	82	71	73	69	66	78	64

Rem.: The concentration THC they are writed on equivalent of fictitious hydrocarbon C_1H (i.e. 3x value of measured C_3H_8 concentration).

- The thermodynamic parameters of engine working cycle at running on PF and LPG are practically coincident (combustion pressure, variability working cycle, ...).
- Exhaust gases temperatures at full-load conditions with mixture enrichment (similar to petrol operation) are lower while running on LPG compared to engine running on PF.
- To achieve optimal fuel consumption and exhaust emissions, different air/fuel ratios are needed for LPG than for petrol; ECU should therefore allow for individual air/fuel ratio settings for each fuel.

Acknowledgments

Published results were acquired using the subsidization of the Ministry of Education of the Czech Republic for project 1M6840770002 – Josef Božek Research Centre for Engine and Vehicle Technologies II.