ISSN 1392–1207. MECHANIKA. 2016 Volume 22(1): 44–50

Fuel dosage irregularity of LPG pulse vapor injectors at different stages of wear

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crossref http://dx.doi.org/10.5755/j01.mech.22.1.13190

1. Introduction

Oil crisis and the environmental concerns add to the pace at which alternative fuels for transport applications are sought. Experimental and simulation research is conducted that evaluates the applicability of different types of alternative fuels that could be safely used in engines from the transport sector. The Alternative Engines Fuels Act guarantees that alternative fuel vehicles are specially treated when calculating the fuel consumption. It is to secure greater production and use of alternative fuels by manufacturers [1]. Corporate average fuel economy is an important tool in the policy of reduction of brake specific fuel consumption.

The continuing trend of reduction of fuel consumption forces a reduction of vehicle weight, optimization of aerodynamics or application of more efficient engines [2], let alone tires of reduced rolling forces. Additionally, multiple injection poses a serious problem when attempting to convert an engine to LPG fuelling due to very short injector opening times that are very often out of range for LPG vapor injectors.

A reduction of the emission of HC and CO (65% and 50% respectively) has been observed for LPG fueling at a minuscule reduction of thermal efficiency compared to gasoline fueling [3, 4]. The values of the environmental indexes heavily depend on the LPG gasoline proportions for some fueling systems (e.g. direct injection) [5]. Alternatively fueled engines utilizing LPG vapor multipoint injection produce power by approx. 4% lower than it is in the case of conventional fueling [6].

LPG fueling under low temperatures has also been positively verified [7, 8]. Attention has been drawn to the problem of LPG flow in the fuel rail [9-11]. Research has also been carried out on control algorithms and smooth control of this kind of fueling systems [4, 12]. The fundamental principle of operation of each fueling system (engine) is the fuel quality. In the case of gasoline, it is controlled by legislation [13] but in the case of LPG the issue is not yet resolved.

Research methods used for the analysis of the process of LPG injection are varied. Engineers observe the injected LPG fuel [14, 15] as well as the pulsations in the fuel rail [14]. The application of heat flow sensors enables characterizing the location and impact level of the fuel upon injection [16]. Another group of research is the technique of laser diffraction and laser-induced-fluorescence used in the analysis of fuel atomization [17-22].

Currently conducted research works are largely devoted to the operation of LPG pulse vapor injectors, which is forced by the growing market share of direct injected engines (due to the specific design of the injector and environmental standards, indirect injection of vapor LPG would not be make sense). Alternative fueling such as LPG is characterized by one more feature - the price of LPG itself. This is the main reason for converting conventional fueling systems to LPG fueling. Majority of ‘older vehicles’ are fitted with multipoint vapor LPG injection systems. A common malfunction in these systems is engine misfires, the reason for which may be the irregularity of fuel injector dosage, hence the author’s attempt to assess this parameter for different wear stages of the equipment. The problem of fuel dosage irregularity has been mentioned in [23].

2. Subject of the research

Because the tests were to show the level of vapor LPG fuel dosage irregularity of the tested objects of various manufacturers, the individual models were encoded. Only the type of control valve and some selected technical parameters were disclosed as shown in Table 1 (this was done to avoid direct comparisons of individual models that could endorse certain manufacturers).

Table 1

Selected technical data of the tested objects

No.	Code	Valve	Flow relative to the piston	Resistance, Ω	Nozzle, mm
brand new					
1	I-1	plunger	transverse	2.00	3.20
2	I-2	plunger	transverse	2.00	3.20
3	I-3	plunger	transverse	1.90	3.20
4	I-4	plunger	longitudinal	1.90	original
5	I-5	plunger	longitudinal	1.25	original
6	I-6	plunger	transverse	1.90	original
7	I-7	plunger	transverse	2.00	2.80
8	I-8	plate	transverse	2.30	4.00
already in operation					
1	II-1	plunger	longitudinal	1.25	2.50
2	II-2	plunger	transverse	3.00	4.00
3	II-3	plunger	transverse	3.00	3.20
4	II-4	plunger	transverse	3.00	3.20
5	II-5	plunger	transverse	2.00	original
6	II-6	plunger	transverse	2.80	3.20
7	II-7	plunger	transverse	2.20	4.00
end-of-life (worn)					
1	III-1	plunger	transverse	3.00	3.20
2	III-2	plunger	transverse	3.00	3.20
3	III-3	plunger	transverse	2.00	3.30
4	III-4	plunger	transverse	3.00	3.20
5	III-5	plunger	transverse	3.00	3.20

3. Research methodology

The research methodology consists in observing the dynamic response of the system to a signal with unit step functions. In this case (Fig. 1), the air from the pneumatic system flows to the air preparation system *1* fitted with a regulator and a dehumidifier. Then, the air flows through an electro valve *2* to the tank *3*, where the overpressure value responsible for the flow to the measurement tanks *6* is set at the start of the measurement. The medium flowing from tank *3* to tanks *6* goes through electro valves of the tested injectors *4* controlled with a chipset *5* based on STAG 300 Premium by AC LLC.

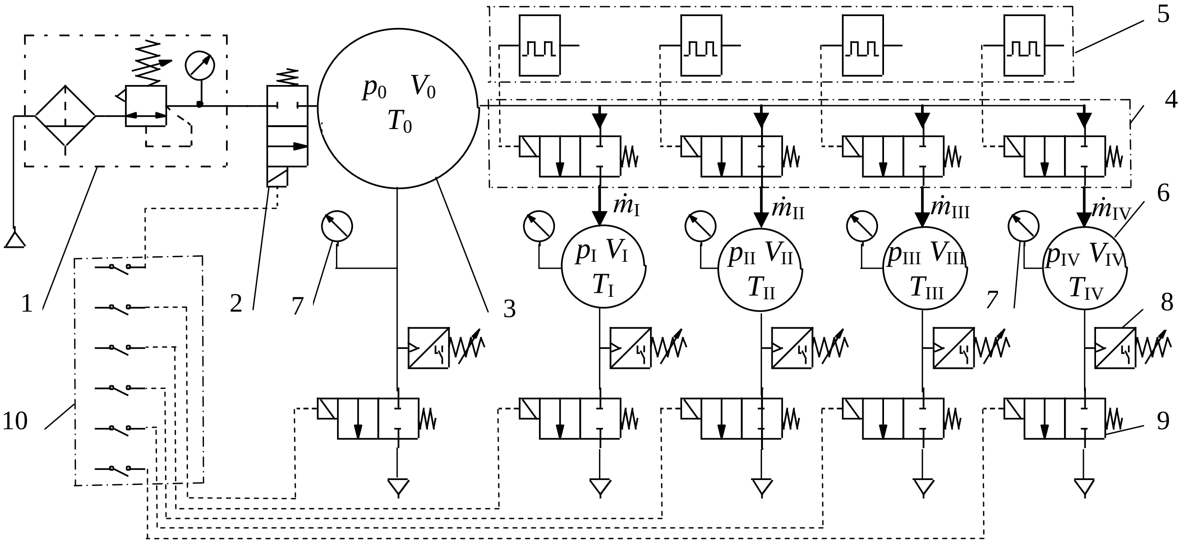


Fig. 1 Structural schematics of the test stand: *1* – air preparation system, *2* – air bleed electro valve, *3* – feeding tank, *4* – test object (a set of four injectors), *5* – injector control system, *6* – filled tank, *7* – pressure gauge, *8* – pressure sensors, *9* – air bleed electro valves, *10* – electro valve control system

The cyclicity of the operation of the electro valves with a closed valve that feeds the air to the tank *3* results in a pressure drop in that tank and a pressure growth in the tank *6*. The analysis of the course of pressure changes in the tanks allows an evaluation of the flow capacities of the tested object with the use of adequate mathematical model. This type of method is successfully used when determining the flow characteristics of the components of brake systems [23].

For the mathematical description of the process occurring within the test stand a concentrated elements method [24] was used, where, based on the air mass balance (replacing vapor LPG) the flow capacities of a given object are assessed.

Due to the fact that the flow process is highly complex in terms of the occurring phenomena, certain assumptions have been introduced, the most important of which are:

- air is treated as an ideal gas of constant specific heat;
- the flow is frictionless and there is no heat exchange to the environment;
- the state of the air is constant in a given cross-section and depends on time;
- the temperature of the flowing medium is constant [25];
- the tested portion is treated as a pipe of a constant cross-section;
- the connections of the individual elements of the tested object are perfectly airtight.

Bearing the above assumptions in mind, at isentropic flow in an adiabatic shield, using the mass balance we can notate the following:

$$\left.\begin{aligned}&\frac{dm_0}{dt} = -\dot{m}_{\mathrm{I}} - \dot{m}_{\mathrm{II}} - \dot{m}_{\mathrm{III}} - \dot{m}_{\mathrm{IV}};\\ &\frac{dm_{\mathrm{I}}}{dt} = \dot{m}_{\mathrm{I}}; \quad \frac{dm_{\mathrm{II}}}{dt} = \dot{m}_{\mathrm{II}}; \quad \frac{dm_{\mathrm{III}}}{dt} = \dot{m}_{\mathrm{III}}; \quad \frac{dm_{\mathrm{IV}}}{dt} = \dot{m}_{\mathrm{IV}}.\end{aligned}\right\} \qquad (1)$$

Change of air mass in individual tanks:

$$\frac{dm_i}{dt} = \frac{V_i}{\kappa R T_i} \cdot \frac{dp_i}{dt}. \qquad (2)$$

Air mass flow going through local resistance:

$$\dot{m}_i = (\mu A)_i \frac{p_0}{\sqrt{RT_i}} \varphi_{max}(\sigma)\, f(\sigma), \qquad (3)$$

where p_i is pressure in measurement tank; V is volume; $(\mu A)_i$ is conductance; T_i is temperature; R is gas constant; κ is adiabatic exponent; $\varphi_{max}(\sigma)$ is maximum value of St`Venant and Wantzel function; $f(\sigma)$ is dimensionless function of flow, the form according to Miatluk–Avtuszko [24], adjusted by the author, $f(\sigma) = 1.4\,(1-\sigma\,/\,(1.4-\sigma))$; $\sigma = p_{in} / p_{out}$, and index i relates to 0, I…IV.

Determining the throughput ($\mu A_{\mathrm{I...IV}}$) from the course of the dynamic characteristics allows an evaluation in the entire tested range determined by the pressure difference at the start of the measurement, which is vital because this difference during operation varies widely.

The system of differential Eq. (1) was solved numerically with the implicit trapezoidal method combined with reverse differentiation, using Matlab.

The throughputs ($\mu A_{\mathrm{I...IV}}$) were determined in the course of the identification, based on the recorded and calculated courses of pressures. To this end, a non-linear regression was used, minimizing the FPE_1 estimator through the Nelder-Mead simplex, until the required calculation accuracy was obtained (10^{-6}).

$$FPE_1 = \frac{j+l}{j(j-1)} \sum_{i=l}^{j} \left(p_{exp} - p_{mod} \right)^2 , \tag{4}$$

where j is number of points of the identified curve; l is number of significant points in the model; p_{exp} is experimental pressure; p_{mod} is modeling pressure.

The coefficient of determination adjusted to the degrees of freedom:

$$R^2 = 1 - \frac{j-l}{j-1} \frac{\sum_{i=1}^{j} \left(p_{exp} - p_{mod} \right)^2}{\sum_{i=1}^{j} \left(p_{exp} - \overline{p_{mod}} \right)^2} . \tag{5}$$

The average error:

$$FPE_2 = \frac{1}{j} \sum_{i=1}^{j} \left| p_{exp} - p_{mod} \right| . \tag{6}$$

The maximum error value:

$$FPE_3 = MAX \left| p_{exp} - p_{mod} \right| . \tag{7}$$

The calculation procedures have been written in the Matlab code, the Guide add-on according to the calculation schematics has been shown in Fig. 2.

A coefficient of unevenness of the injector dosage Q_R was proposed:

$$Q_R = \frac{\sum_{i=1}^{c} \left| q_i - q_{av} \right|}{\sum_{i=1}^{c} q_i} , \tag{8}$$

where q_i is mass flow rate of the section; q_{av} is average mass flow rate of the section and c is number of section.

Having the results of the measurements, the mass and volumetric flow have been determined along with the mass per cylinder cycle. Fig. 3 presents a prototype of a test stand with a communication panel of the identification software.

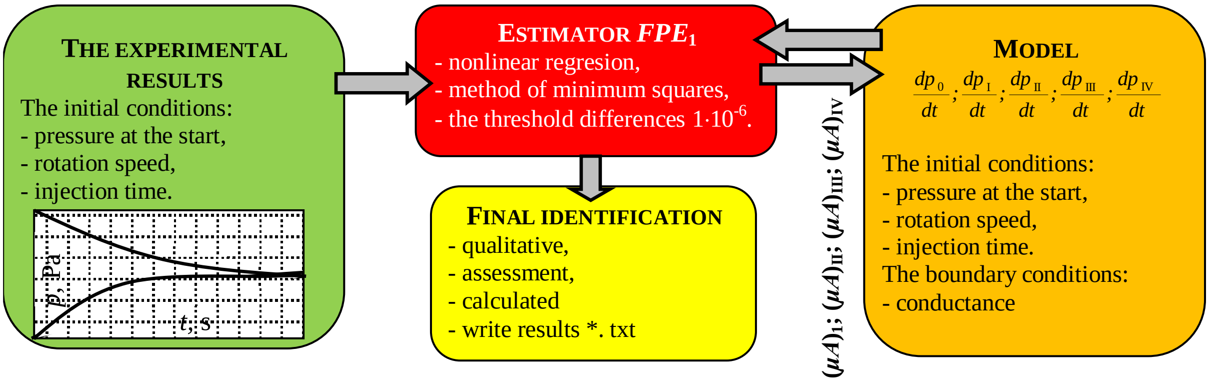
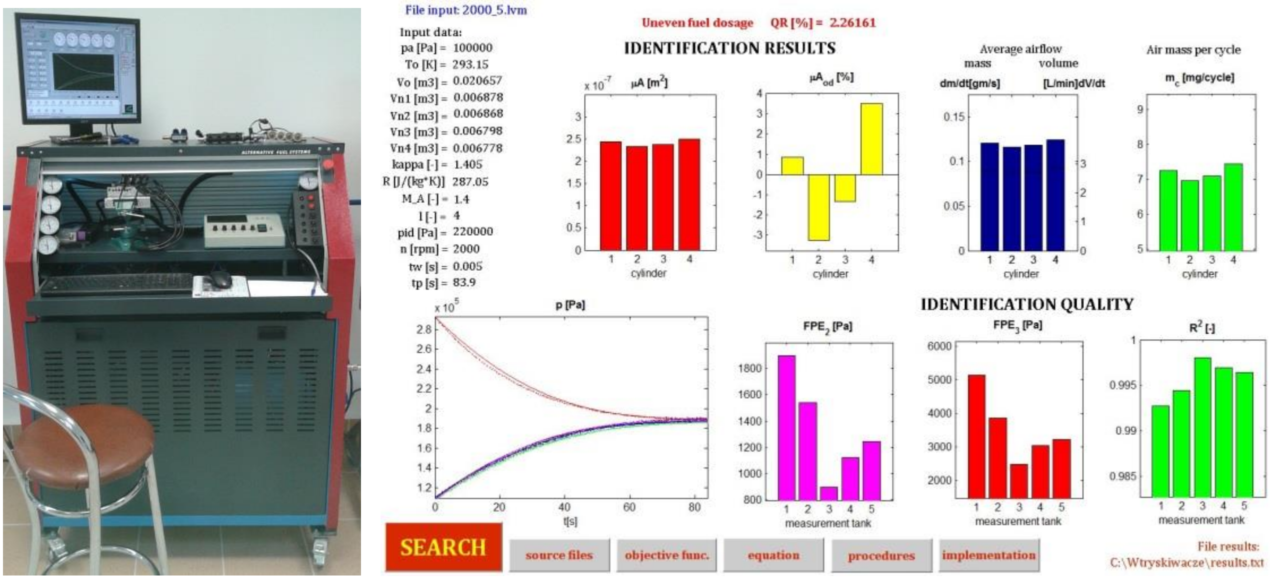


Fig. 2 Block diagram of the identification program in Matlab-Simulink-Guide



File input: 2000_5.lvm

Input data:
pa [Pa] = 100000
To [K] = 293.15
Vo [m3] = 0.020657
Vn1 [m3] = 0.006878
Vn2 [m3] = 0.006868
Vn3 [m3] = 0.006798
Vn4 [m3] = 0.006778
kappa [-] = 1.405
R [J/(kg*K)] 287.05
M_A [-] = 1.4
I [-] = 4
pid [Pa] = 220000
n [rpm] = 2000
tw [s] = 0.005
tp [s] = 83.9

Uneven fuel dosage QR [%] = 2.26161

File results: C:\Wtryskiwacze\results.txt

a b

Fig. 3 Prototype of a test stand (a), communication panel of the identification software (b)

The courses of the pressure changes in the tanks were recorded using the Honeywell sensors, measurement card by National Instruments and LabVIEW Developer Suite software. The opening of the electro valves of the injectors was done in a repetitive sequence maintaining 4 ms of full signal after which modulation with PWM took place (Fig. 4).

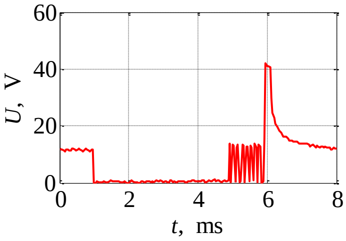


Fig. 4 Example voltage on the terminal of one of the injectors

4. Results and discussion

The tests were carried out according to the schematics presented in Table 2. For each tested component, the same engine speeds and injector opening times were set. At operating frequencies corresponding to high engine speeds and long injector opening times the control software would indicate permanent opening, hence these measurements were not included in the analysis.

The recorded courses of pressure were subject to the processes of numerical identification. A proper selection of the throughput, further used in the calculations can ensure high convergence of the experimental and model research (Fig. 5).

Table 2

The research range

t_{inj}, ms	n, rpm					
	700	1000	2000	3000	4000	5000
2.5	X	X	X	X	X	X
5.0	X	X	X	X	X	X
10.0	X	X	X	X	X	X
15.0	X	X	X	X	X	X
20.0	X	X	X	X	X	
25.0	X	X	X	X		
30.0	X	X	X	X		

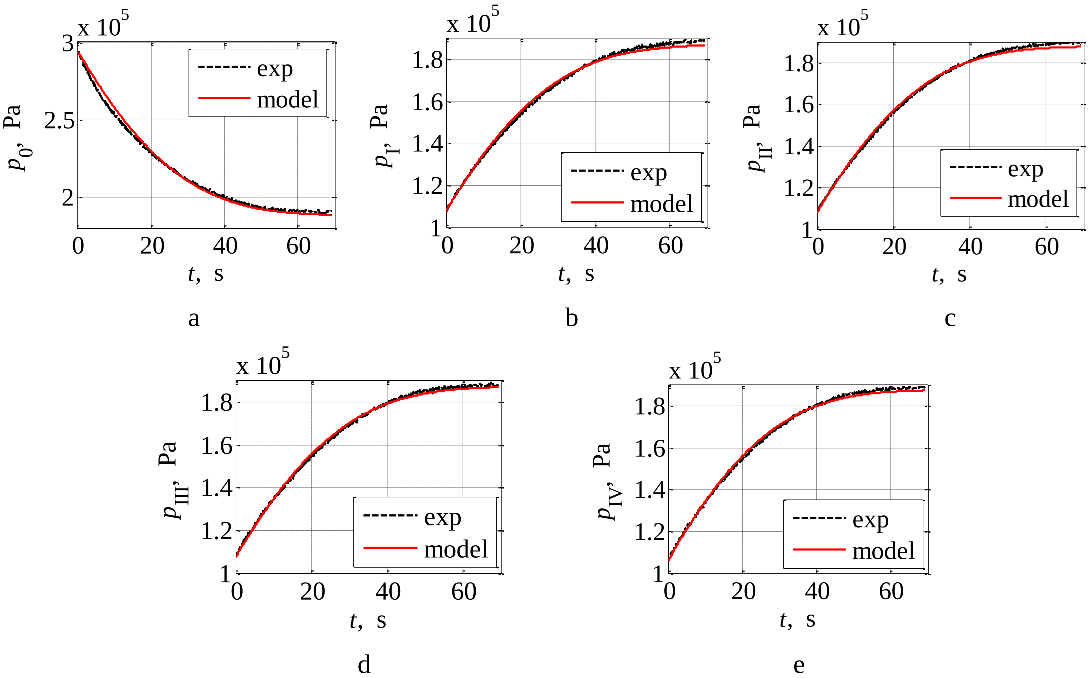


Fig. 5 Sample comparison of the model courses with the experimental ones at the opening time of 5 ms and engine speed of 2000 rpm: a - empty container; b-e - filled containers

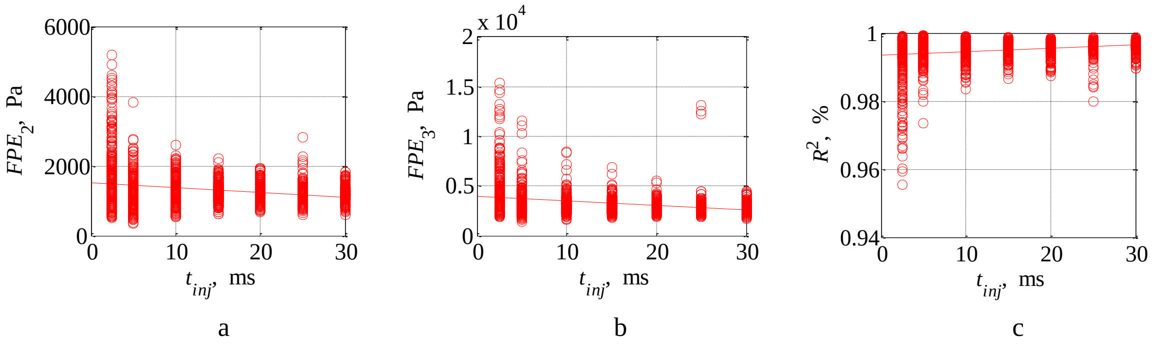


Fig. 6 Qualitative evaluation of the identification process: a - average error; b - maximum error; c - coefficient of determination

Upon qualitative evaluation of the identification process (Fig. 6) the following were observed: an averaged value of the mean error on the level of 1320 Pa (approx. 0.6% of the tested range, 2.5% max), maximum error 3292 Pa (approx. 1.6% of the tested range, 7.5% max) and the regression coefficient 0.9951 (minimum 0.9568). Greater errors occurred when a comparison was carried out to the emptied tank.

Having the flow rates (mg/cycle) of the individual sections calculated in the numerical identification, their flow characteristics were determined (Fig. 7).

Linearly approximating the flow characteristics, the values of the coefficient of inclination of straight *a* and the crossing points with axis *q* – *b* were determined (Table 3). Upon qualitative evaluation of the approximation, the coefficient of determinance mostly exceeded 0.995. Having values *a* and *b* it is possible to determine the zero time $t_0 = -b/a$ [27]. It does not mean, however, that this time will guarantee that the injector will open at such a short impulse. On the other hand, the positive value of parameter *b* pushes the zero time towards negative values.

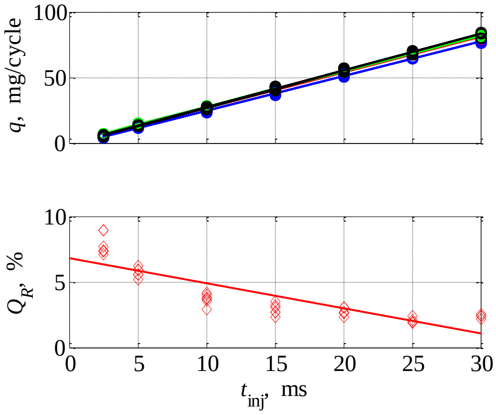


Fig. 7 Example flow characteristics of the injector together with its determined irregularity

Table 3

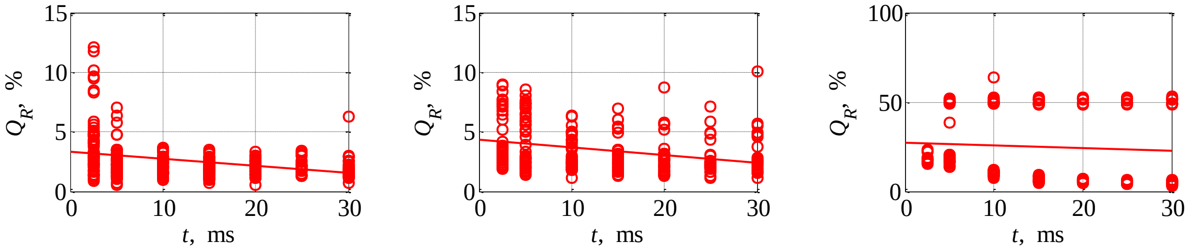
Significant parameters of the flow characteristics and fuel dosage irregularity

Code	section I		section II		section III		section IV		Q_R
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	%
brand new									
I 1	2.2841	-2.3198	2.2116	-2.8369	2.1841	-2.4159	2.3301	-2.8032	3.2687
I 2	2.5320	-1.8462	2.4672	-2.1808	2.4878	-2.3160	2.5760	-2.2878	2.3911
I 3	2.1475	-2.5490	2.2049	-2.5901	2.1045	-2.4066	2.1476	-2.2451	1.8473
I 4	2.1166	-1.8092	2.0925	-1.8044	2.0553	-1.7671	2.1851	-1.9583	1.7151
I 5	1.6216	-0.9680	1.6064	-1.0965	1.5824	-0.9522	1.6429	-0.9625	1.6093
I 6	2.2765	-1.8728	2.2096	-1.8746	2.1492	-1.7207	2.3397	-2.1479	2.6076
I 7	2.3079	-1.6703	2.3054	-1.1452	2.2572	-1.1508	2.3926	-1.3707	2.5093
I 8	1.9440	0.8109	1.9967	-0.0476	1.9466	-0.5017	2.0943	-1.1646	3.8653
already in operation									
II 1	2.3141	-0.2750	2.2730	-0.7376	2.2121	-0.2260	2.3428	-0.6825	2.0123
II 2	2.2927	-2.6991	2.2057	-2.5609	2.2530	-1.9734	2.2599	-2.6199	2.4368
II 3	2.1980	-0.6148	2.1717	-0.3473	2.1243	-0.8067	2.3290	-1.2722	2.7183
II 4	2.1566	0.2663	2.2088	-0.2927	2.2011	1.5217	2.1176	-0.0651	4.3377
II 5	2.0426	-3.2973	1.9089	-3.3309	2.1401	-3.3497	2.3300	-4.3596	6.1449
II 6	2.3582	0.0243	2.4108	-0.5260	2.3328	-0.5205	2.4889	-0.2179	2.5222
II 7	2.7407	-0.6587	2.6497	-1.7014	2.7304	0.3446	2.8119	-1.0037	4.1313
end-of-life (worn)									
III 1	2.2606	-2.4283	2.3468	3.0108	2.1436	-1.0874	2.2144	-1.7865	9.8680
III 2	1.3095	-1.6858	0.0203	-0.0908	1.8973	-3.6192	2.3418	-2.8601	51.5230
III 3	1.9995	-3.0139	2.1748	-0.7849	1.7915	1.1769	0.0311	-0.0533	49.2732
III 4	1.6944	4.8807	1.6923	3.3836	1.6597	-0.2131	1.7043	2.8096	9.8288
III 5	2.1265	1.8459	2.0010	-0.7366	1.9275	-1.1005	2.0749	1.1214	10.4342

For each of the cases, based on the values of unit flow rates (mg/cycle) the irregularity of fuel dosage (Table 3) was determined following the relation (8). Comparing the graphic results of the calculations of fuel dosage irregularity at different stages of wear (Fig. 8), we can observe that brand new injectors are characterized by an averaged value of Q_R on the level of 2.5%, injectors already in operation – 3.4% and end-of-life (worn) injectors – 25%. In the last case, in the components III 2 and III 3 issues with the operation of one section have been observed. If they were eliminated from the analysis, we could state that the outstanding ones in the group had their Q_R on the level of 12.5%. It is noteworthy that the tested components came from different price and quality groups, which is why some brand new injectors had worse results that the worn ones.

Referring the dosage irregularity values of the vapor LPG injectors to those of gasoline ones fitted in multipoint injection systems, it has been observed (based on the test performed on a test stand described in [26]) that the latter had Q_R on the level of 0.25% for new injectors, 0.25…0.5% for the injectors in operation and over 5% for the worn injectors.

It should be noted that the comparison only aimed at drawing attention to the problem as the tested population is too small for statistical purposes. Research is continued in this direction to extend the database of the results.



a b c

Fig. 8 Fuel dosage irregularity of LPG pulse vapor injectors brand new (a), already in operation (b) and end-of-life (c)

6. Conclusions

The developed prototype test stand, in combination with the numerical identification allows determining of the flow characteristics of the vapor LPG injectors. Following the calculations, it is possible to evaluate the fuel dosage irregularity of the injectors. Additionally, a calibration of the injectors is possible or a periodical service in order to make the flow characteristics of individual sections uniform. In the course of the research, based on a selected group of objects the author has observed the following:

1. Brand new injectors were characterized by a 2.5% dosage irregularity on average, some of which were below 2%.

2. Injectors in operation, at different stages of wear, had an average irregularity on the level of 3.4%, 2 % minimum.

3. End-of-life (worn) injectors had very poor results of 25% of dosage irregularity, mainly due to the recurring issues of misfire.

4. The qualitative evaluation of the throughput identification based on the courses of pressure has shown high accuracy, the averaged values of mean error were 0.6%, maximum – 1.6%, and the coefficient of determinance – 0.995.

5. A similar situation occurred for linear approximation of the flow characteristics – the coefficient of determinance was $R^2 \geq 0.995$.

6. In the future, the author plans to extend the test stand by a temperature measurement system and modify the identification software to allow for this parameter

Acknowledgment

The investigations described in this paper are a part of the research project No S/WM/2/13 realized at Bialystok University of Technology.

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D. Szpica

FUEL DOSAGE IRREGULARITY OF LPG PULSE VAPOR INJECTORS AT DIFFERENT STAGES OF WEAR

Summary

The idea of converting gasoline engines to LPG alternative fuelling results mainly from the fuel price. The paper presents the results of flow research performed on a prototype test stand. In the process of numerical identification and relevant calculations the irregularities of fuel dosage of LPG vapor injectors have been determined. Injectors of different stage of the wear process have been subjected to the test with a view to showing a difference between newly manufactured injectors, injectors in operation as well as end-of-life (worn) injectors. The said irregularity is the primary cause of engine misfires.

Keywords: internal combustion engine, fuel supply, alternative fuels, flow research.

Received September 20, 2015
Accepted January 19, 2016