RESEARCH ON THE INFLUENCE OF LPG/CNG INJECTOR OUTLET NOZZLE DIAMETER ON UNEVEN FUEL DOSAGE

Dariusz Szpica

Dept of Mechanical Engineering, Bialystok University of Technology, Poland

Abstract. The paper presents an original flow research methodology in LPG/CNG injectors. When adapting alternative LPG systems of the IV generation, very often the injector nozzles are adapted individually to change the flow parameters. Hence, in the paper the author attempted to evaluate the influence of the injector nozzle diameter (min and max) on the uneven fuel dosage. The determined average throughputs were 0.0235–3.3683 mm^2. The averaged difference in the unevenness reached 0.0419%, its minimum value is 0.0694 and the maximum is 0.7703, which can influence the correction of the mixture composition made through the oxygen sensor. Additionally, the flow characteristics of the injectors for both diameter variants have been presented, showing the necessity of inspecting the component after nozzle boring.

Keywords: combustion engine; fuel supply; alternative power systems; LPG injectors; uneven fuel dosage.

Glossary

(μA) – conductance, throughput [m^2];

Δt – measurement step [s];

$\overline{(\mu A)}$ – average conductance in the supply process [m^2];

$\bar{p}_m$ – average share of the modeling pressure [Pa];

μ – flow coefficient;

$f(\sigma)$ – dimensionless flow function;

BSFC – Brake Specific Fuel Consumption [g/(kWh)];

k – measurement point;

l – number of significant points in the model;

LU – speed of unevenness [1/s^{-2}];

m – number of points of the identified curve;

p – pressure [Pa];

R – gas constant [J/(kgK)];

n – rotation speed [rpm];

t – time [s];

M – engine torque [Nm];

T – temperature [K];

V – volume [m^3];

v_m – sound propagation in a stationary gas [m/s];

α – angular acceleration [1/s^2];

κ – adiabatic exponent;

σ – pressure ratio for and against local resistance;

φ – angle [deg];

$\varphi_{max}(\sigma)$ – maximum value of the Saint Venant and Wantzel's function.

Index

a – atmospheric;

t – tank;

e – experimental;

m – model;

i, j – step.

Nomenclature

LPG – Liquefied Petroleum Gas;

CNG – Compressed Natural Gas;

FPE – Final Prediction Error.

Introduction

Multi-cylinder high-speed spark ignition internal combustion engines are characterized by different operation of the individual cylinders – see for example Müller (1967a, 1967b), Rawski (1980), Szpica (2008). This may cause irregular engine operation and elevated emissions, which results in difficulties maintaining the external parameters on a required level.

Out of many factors influencing the variations in the individual cylinder operation the following are the most important:

- composition of the air fuel mixture in the individual cylinders represented by the air excess coefficient;

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– amount of air fuel mixture in the individual cyl-
   inders represented by the filling coefficient;
– air tightness of the cylinders represented by the
   pressure drop;
– energy and ignition angle;
– valve timing;
– precision of workmanship.

Based on the analysis of literature, the first two fac-
tors can be seen as the most significant, i.e. the compo-
sition and amount of air fuel mixture in the individual
cylinders, both, heavily dependent on the preparation
and feed of the mixture in the manifold.

The problem with even cylinder feed can be caused
by a lack of work repeatability in the succeeding engine
operation cycles, as shown by Tichy (1994). He analyzed
the succeeding cycles during a constant load (Fig. 1a)
and developed the histogram of the cycle disruption LU_j
Eq. (1), (Fig. 1b):

$$LU_j = \frac{\Delta\alpha_j}{\varphi} = \frac{t_{j-1} - t_j}{t_j^2 \cdot t_{j-1}} - \frac{t_{j-2} - t_{j-1}}{t_{j-1}^2 \cdot t_{j-2}} \,. \tag{1}$$

These two factors (the unevenness of fuel feed to
the individual cylinders and the lack of repeatability)
are responsible for the vibrations of the engine and the
entire drivetrain (increased noise). The topics concern-
ing the uneven air supply to the engine have already
been presented Rawski (1980) and Szpica (2008) where
the authors state that it did not exceed the average 1%.
Ranges (at increased engine speeds) at which the une-
venness reached 10% were also determined. The uneven-
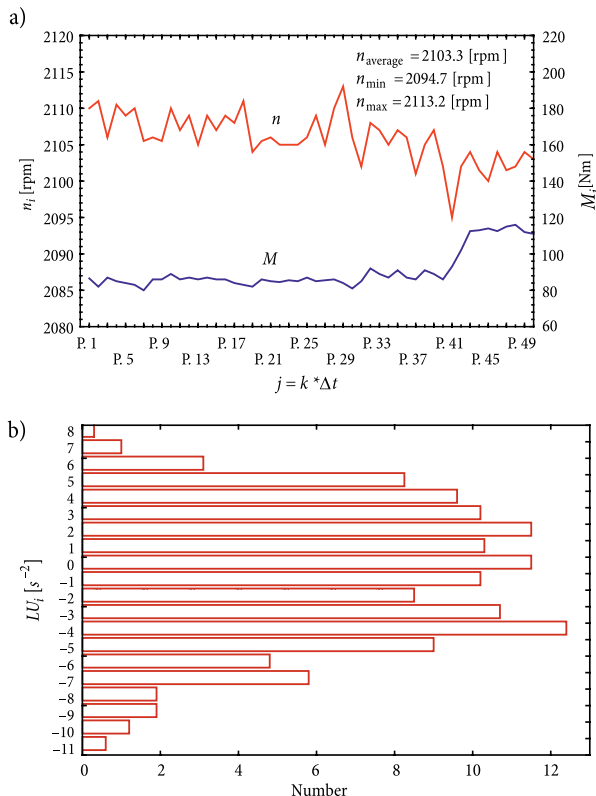ness of the engine fuel feed is not commonly described

in literature. Szpica (2013) presents the uneven dosage
by the LPG injectors. Szpica and Czaban (2014) shows
sample comparison results of petrol and LPG injectors.
In this work, the author states that for petrol injectors
the dosage unevenness oscillates around 0.25% for new
components and up to 5% for used ones. However, new
LPG injectors generate the unevenness level at about
1%, whereas the used ones – at approximately 10% (this
value is often exceeded).

The dosage unevenness under consideration leads
to a situation that the increases do not counterbalance
the drops, as confirmed by Zimmerman *et al.* (1972).
This applies to the external parameters, i.e. effective
pressure p_e, economic parameters BSFC (Fig. 2 a) and
exhaust gas composition HC, CO, NO_x, O_2 (Fig. 2b, c).

It is thus important to consider not only the new
injectors, but also the used ones. The unique diagnostic
stand, proposed by Szpica and Czaban (2009), Szpica
(2011, 2013) allows a quick assessment of the injectors
of LPG in its gaseous phase against its flow.

Current literature focuses on the injection of LPG
in the liquid phase because this phase is required by
modern engines. The research covers algorithms of
smooth control (Sim *et al.* 2004, 2005; Cho, Min 2004)
or problems of liquid LPG flow in the fuel rail (Yeom
et al. 2009; Senda *et al.* 1994; Oliveira Panão *et al.* 2013).
The research also covers observations of the injection of
liquefied LPG (Oliveira Panão *et al.* 2013; Park 2005)
(that are subsequently compared to that of petrol), the
LPG pulsation in the fuel rail (Oliveira Panão *et al.* 2013)
or cold starts (Kim *et al.* 2013). The authors propose new
injector solutions (Kushari 2010) and service methods
(Robart *et al.* 2001). An increased exhaust gas emission
is observed at different LPG – petrol ratios for some fuel
systems (Gumus 2011).

Despite the fact, that modern direct injection en-
gines require specific LPG fuel systems (requiring the
supply of a liquid LPG phase), a large number of vehi-
cles use gaseous phase LPG injectors (IV generation).
Because of their design, gaseous phase LPG injectors are
most frequently adjustable and can even be removed for
maintenance. There exists a spare part market, but not
for every type. A small part of literature (Majerczyk,
Radzimirski 2012) touches upon the uneven LPG injec-
tor dosage, blaming the control algorithms and show-
ing up error codes registered in the memory. Some LPG
calibration software enables the determination of the
injector dosage unevenness, without removing the com-
ponents. The example of the software includes *Diego LS*
enabling the calibration based on engine control system
indications.

Comparing petrol systems and I, II and IV gen-
eration LPG systems in terms of external indicators, it
can be stated that differences in the maximum power
are 5.71%, maximum torque is 7.27% to the detriment
of LPG (Czaban, Szpica 2010).

Author developed an original methodology for the
assessment of the influence of the LPG/CNG injector
outlet nozzle diameter on the fuel dosage. This method-
ology would be used not only in laboratory conditions,
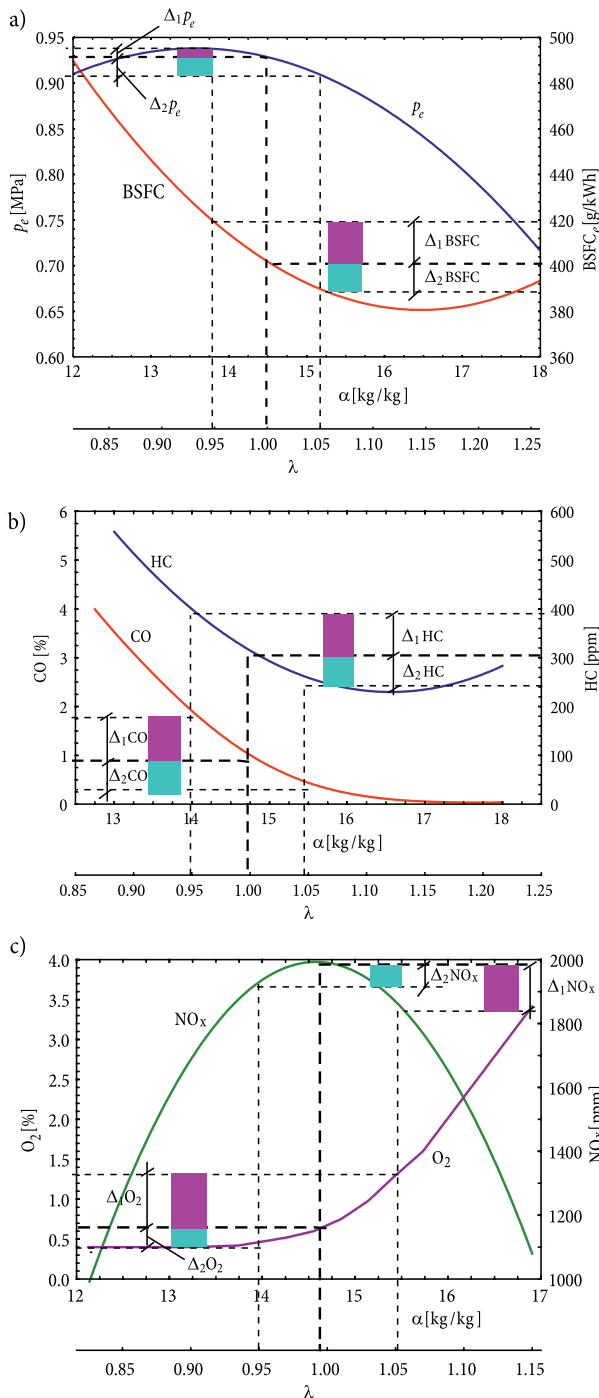but also during the new product inspection, or in the

a)

b)

Fig. 1. Uneven engine speed n_i and torque M_i at:
a – a constant load; b – uneven operation (Tichy 1994)

Fig. 2. Increases and drops of: a – p_e and BSFC against their values at $\lambda = 1$; b – HC and CO against their values at $\lambda = 1$; c – NO$_x$ and O$_2$ against their values at $\lambda = 1$ (Zimmerman *et al.* 1972)

workshops dealing with the operation and repair. That is why one of the criteria considered during elaboration of the stand was its price. The research issues mentioned in the paper are interesting for the companies manufacturing the subjected subsystem, in which very common practice is the quick verification of injectors' uneven dosage. After introducing the multi-point gasoline injection and adaptive systems it was stated that the problem of uneven fuel dosage was solved. However, in the

case of alternative powering systems, especially with periodic LPG/CNG injection, the less precise subsystems are used, what is often connected with cost minimization. They are characterized with lower repeatability, the problem of uneven powering turns back. That is why the one of the ways of the regulation of their flow, the calibrated outlet nozzles are used. This caused the aim to preliminarily assess the influence of injector nozzle diameter on the whole system dosage unevenness, considered as the precise one basing on the information from the LPG/CNG industry branch.

1. Material and Methods

1.1. Subject of the Research

The research object was an injection rail by ALEX. In the rail, there were 4 brand new piston BARRACUDA LPG/CNG injectors of serial numbers SN: 130204140103, 130204135634, 130204135659, 130204140516. The injectors came as a set with a BD124P BARRACUDA tray and components included in the set (Fig. 3).

Fig. 3. Subject of the research – a system of injectors

Basic technical data of the tested injectors have been presented in Table 1.

For the research, the authors used calibration nozzles with a minimum cross-section. Other technical data have been shown in Table 1.

Table 1. Basic technical data of the tested injectors

Secondary technical data		
max flow rate at 1.2 bar	Nl/min	115 ±1
nozzle size	mm	max 2.8 min 1.2
coil resistance	Ω	1.9 ±5%
opening time	ms	1.9
closing time	ms	1.2
max peak current	A	4
max hold current	A	2
operating working pressure	bar	0.2÷4.2
max working pressure	bar	4.5
operating temperature	°C	−20÷120
operating voltage range	VDC	6÷18
warranty	km	100 000
life-span of stroke	>500 million cycles	
connector	SuperSeal	
homologation	E8 67R-01 6407; E8 110R-00 6408	

1.2. Research Methodology

In the course of the study, an indirect container method was applied in which the flow was forced by the pressure difference between the empty tank and the filling tanks of the range of up to 2 bar. The filled container acted as a flow meter (Rawski 1980; Szpica 2008). For safety reasons, the research was realized using compressed air instead of LPG/CNG. The injection rail was placed on the way of the flowing air. The supply from 1 'large' container was connected to the inlet rail connector and the injector nozzles – to the 4 'small' containers. The openings were realized by the original pulsator simulating actual LPG system operation. After 2.5 ms of the opening time, the PWM signal stimulation occurred. In this way, the actual operating conditions were simulated (commonly during research the opening is realized by a rectangular signal).

The flow investigations aimed at determining the average doses (masses) of air injected through the injectors at a pressure difference of 1.2 bar. The determined parameter, specified as conductance (μA), applies to the entire range under research.

For mathematical description, the author used the focused volume method (Iwaszko 1998; Szpica 2008; Shampine 1997). In the course of the discretization, two generalized members were used, i.e. local resistance and focused volume. On this basis, the measurement stand schematics was created (Fig. 4).

Assuming that the flow is isentropic in an adiabatic shield (Szpica 2008, 2013) and the medium temperature during the whole process is constant (Iwaszko 1998), the system of differential equations was written showing the pressure change in the measuring tanks acting as a flow meter – Eq. (2). In the description the Metlyuk and Avtushko (1980) flow function $f(\sigma)$ was used with a changed parameter – Eq. (3). Originally, the parameter value of the function was $a = 1.4$. As the criterion of the elaboration, average and maximum error values were assumed (relations shown in the following part).

$$
\begin{cases}
\dfrac{dp_{t0}}{dt} = \dfrac{\kappa R T_{t0}}{V_{t0}}\left(-\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4\right); \\[2mm]
\dfrac{dp_{t1}}{dt} = \dfrac{\kappa R T_{t0}}{V_{t1}}\left(\dot{m}_1\right); \\[2mm]
\dfrac{dp_{t2}}{dt} = \dfrac{\kappa R T_{t0}}{V_{t2}}\left(\dot{m}_2\right); \\[2mm]
\dfrac{dp_{t3}}{dt} = \dfrac{\kappa R T_{t0}}{V_{t3}}\left(\dot{m}_3\right); \\[2mm]
\dfrac{dp_{t4}}{dt} = \dfrac{\kappa R T_{t0}}{V_{t4}}\left(\dot{m}_4\right).
\end{cases}
\tag{2}
$$

$$
f(\sigma) = a\frac{1-\sigma}{a-\sigma}, \tag{3}
$$

where:

$$
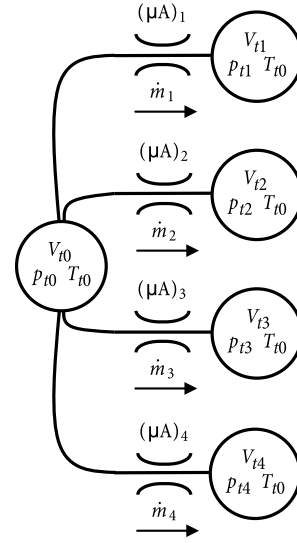\sigma = \frac{p_{i+1}}{p_i};
$$

Fig. 4. Schematics presenting the assumed model of flow in the model test stand conditions for identification purposes

mass flows through local resistances will take the value as in Eq. (4):

$$
\begin{cases}
\dot{m}_1 = (\mu A)_1 \dfrac{p_{t0}}{RT_{t0}} v_{\max}\varphi_{\max}(\sigma)1.4\dfrac{1-\sigma}{1.4-\sigma}; \\[2mm]
\dot{m}_2 = (\mu A)_2 \dfrac{p_{t0}}{RT_{t0}} v_{\max}\varphi_{\max}(\sigma)1.4\dfrac{1-\sigma}{1.4-\sigma}; \\[2mm]
\dot{m}_3 = (\mu A)_3 \dfrac{p_{t0}}{RT_{t0}} v_{\max}\varphi_{\max}(\sigma)1.4\dfrac{1-\sigma}{1.4-\sigma}; \\[2mm]
\dot{m}_4 = (\mu A)_4 \dfrac{p_{t0}}{RT_{t0}} v_{\max}\varphi_{\max}(\sigma)1.4\dfrac{1-\sigma}{1.4-\sigma}.
\end{cases}
\tag{4}
$$

The identification of the conductance parameter (μA) from the dynamic characteristics shows the advantage over the method described in Rawski (1980) based on one point in the characteristics. Rawski (1980) the mass flows were determined based on one of the characteristic points (assumed around the value of the average pressure difference), which led to the conclusion on the uneven cylinder supply (with air). The (μA) parameter applies in the entire studied range; hence, its applicability is higher. While searching for the conductance, a method of non-linear regression was used, minimizing the FPE_1 index by Eq. (5). The minimization was performed numerically through a gradientless method of Nelder–Mead simplex. The minimization was performed with the use of MatLab & Simulink User's Guide (MathWorks 2015), fminsearch procedure (Shampine *et al.* 1997; Smith 2006, Yang *et al.* 2005).

$$
FPE_1 = \frac{m+l}{m(m-1)}\sum_{i=1}^{m}(p_e - p_m)^2. \tag{5}
$$

Using the recorded courses, the author searched for changes in the pressures in the measurement tanks in subsequent iterations of the model courses using the *ode23tb* (*http://se.mathworks.com/help/matlab/ref/*
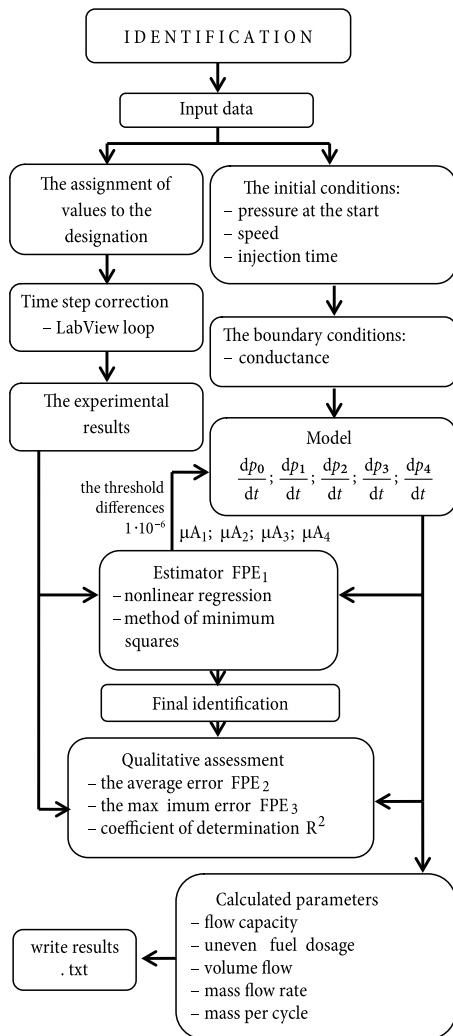
Fig. 5. Block diagram of the identification program in
MatLab & Simulink User's Guide (MathWorks 2015)

ode23tb.html) system of differential equations by Eq. (2).
In the insider MatLab & Simulink User's Guide (Math-Works 2015) terminology, *ode23tb* method is a combination of an implicit Runge–Kutta formula with the first stage – a trapezoidal rule step and the second stage – a backward differentiation formula of the second order (Lagarias *et al.* 1998).

Through a proper selection of conductance $(\mu A)_{1...4}$, we can obtain a high level of experiment and model conformity. The qualitative evaluation of the identification was done through determining of the average and maximum error and the coefficient of determination.

The FPE_2 index representing the average error has been determined by Eq. (6):

$$FPE_2 = \frac{1}{m}\sum_{i=1}^{m}\left|p_e - p_m\right|.$$ (6)

The maximum FPE_3 error value (Eq. (7)):

$$FPE_3 = \mathrm{MAX}\left|p_e - p_m\right|.$$ (7)

The coefficient of determination adjusted to the degrees of freedom R^2 (Eq. (8)):

$$R^2 = 1 - \frac{m-l}{m-1}\cdot\frac{\sum_{i=1}^{m}\left(p_e - p_m\right)^2}{\sum_{i=1}^{m}\left(p_e - \overline{p}_m\right)^2}.$$ (8)

A coefficient of unevenness of the injector dosage Q_R was proposed by Eq. (9):

$$Q_R = \frac{\sum_{i=1}^{4}\left|(\mu A)_i - \left(\overline{\mu A}\right)_i\right|}{\left(\overline{\mu A}\right)_i}\ \left[\%\right].$$ (9)

To obtain a clear and ordered system of communication in the process of identification, an interface shown in Fig. 5 has been developed in MatLab & Simulink User's Guide (MathWorks 2015). The block diagram of the program has been shown in Fig. 5.

A prototype was built (Fig. 6), based on the applied design assumptions and proposals of mathematical model describing the phenomena occurring within the test stand. After filling the container 2, the required injector opening times were realized through the actuation system 6, a result of which was the filling of the containers 3. The courses of the pressure change in containers 2 and 3 were registered using Honeywell sensors (accuracy is 0.25%; full scale is $6\cdot10^5$ Pa), a measurement board by National Instruments NI-USB 6215 and Lab-View 8.5 Developer Suite software. The opening times of the injectors, similarly to the engine speed, were a result of the pulsator settings. Every time before the measurement the rail was 'heated' (it was activated for approximately 10 minutes).

The research was realized according to the schematics shown in Table 2. Each measurement was repeated 3 times and the average value was determined. The test was conducted using two variants: with the calibration nozzles (1.2 mm) and without them (2.8 mm).
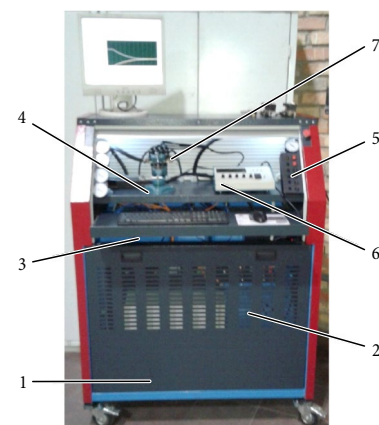

Fig. 6. Research stand (Szpica 2013): 1 – frame with equipment, 2 – measurement supplying reservoir, 3 – filled reservoirs, 4 – rotary vise, 5 – control system of reservoir power and outlet electro-valves, 6 – system forcing the injector opening (STAG-based Premium driver made by AC LLC), 7 – tested injecting element, additional – connecting lines

Table 2. The research range

t_{inj} [ms]	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]
2.5	×	×	×	×	×
5.0	×	×	×	×	×
7.5	×	×	×	×	×
10.0	×	×	×	×	×
12.5	×	×	×	×	×
15.0	×	×	×	×	×
17.5	×	×	×	×	×
20.0	×	×	×	×	×
22.5	×	×	×	×	×

2. Results and Discussion

The dialog box of the identification program (Fig. 7) contains the function buttons allowing access to: selected files, an objective function, relations (equations), procedures/implementations and the visualization of the results of the identification (conductance and uneven injector dosage).

Additionally, the dialog box shows the average mass airflow per cycle. The window also shows the identification quality (FPE_1, FPE_2, FPE_3 and R^2) and the input parameters. The identification is initiated with the search button.

To initiate the identification, the input parameters must be known along with the boundary conditions, as shown in Table 3.
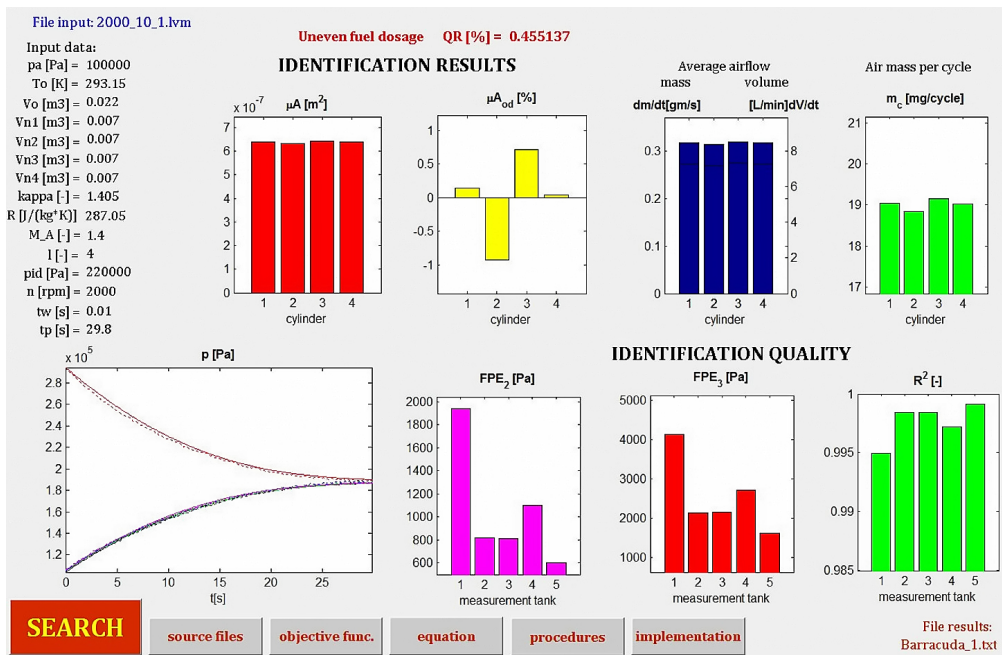

Fig. 7. Software panel for the identification of the flow parameters created in the MatLab & Simulink User's Guide (Szpica 2013)

Table 3. Necessary parameters to initiate the identification

| Input data			
pressure in the measurement tank	p_{t0}	Pa	$3.000\ e^5$
pressure in the measurement tank	$p_{t1...4}$	Pa	$1.000\ e^5$
measurement tank volume	$V_{t1...4}$	m^3	$0.700\ e^{-3}$
measurement tank volume	V_0	m^3	$2.200\ e^{-3}$
air temperature in the measurement tank	T_{t0}	K	293.150
adiabatic exponent	κ		1.400
gas constant	R	J/(kgK)	287.150
sound propagation in a stationary gas	v_m	m/s	$sqrt(\kappa R T_{t0})$
maximum value of the Saint Venant and Wantzel's function	$\varphi_{max}(\sigma)$		0.578
factor function Miatluk–Avtushko	a		1.400
number of points of the identified curve	m		auto
number of significant points in the model	l		4.000
Boundary conditions			
conductance, throughput	$(\mu A)_{1...4}$	m^2	$0.500\ e^{-6}$
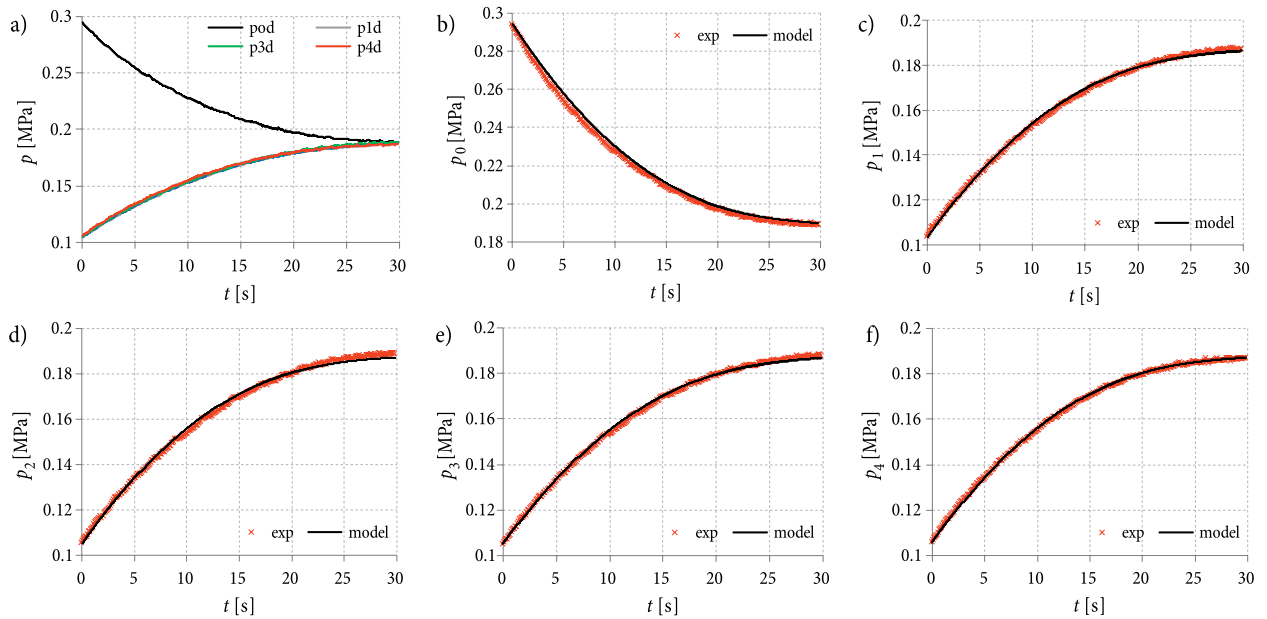
Fig. 8. Sample comparison of the model courses with the experimental ones at the opening time of 10 ms and engine speed of 2000 rpm: a – measurement results; b – empty container; c–f – filled containers

As mentioned, the test was conducted with two variants: with the calibration nozzles (1.2 mm) and without them (2.8 mm). Every measurement was repeated three times, calculating the average value, which was the basis for comparison.

As shown in Fig. 8, by selecting proper conductance $(\mu A)_i$, a high level of compliance of the model courses with the experimental ones could be obtained.

The selection of throughput, which is the basis for the course of the identification, allows, in further stages, the evaluation of the uneven injector dosage based on Eq. (9). The throughput (conductance) is the parameter that applies in the whole range under research and allows determining the mass and volume flow rates or the mass given per working cycle of the engine at a randomly configured inlet-outlet pressure rate.

Fig. 9 shows the flow capability of the investigated LPG/CNG injectors regarding the boundary fitting possibilities (because of the extent of the obtained results only their part, which concerned the first section of the injector, has been presented). Such an approach allows specifying the maximum differences in the throughputs of the studied object. The difference between injectors with no calibration nozzles and those fitted with the nozzles of minimum diameter, results in a difference of the conductance on the level of 57.37%. In the investigated case, both injectors and calibration nozzles were brand new, but the difference in the conductance leads to conclusions related to the boundary differences in the case of contamination with untypical component or inaccurate boring during fitting.

The limit values of the throughput determined during the measurement (Table 4) reach a maximum of 3.3683 mm² for the system without the nozzle and a minimum 0.0235 mm² for the system with the noz-

zle fitted. The average value from all measurements was 1.2166 mm² without the nozzle and 0.5186 mm² with the nozzle fitted. A problem with the fuel dosage in two measurement points was observed: $n = 2000$ rpm, $t_{inj} = 7.5$ ms; $n = 5000$ rpm, $t_{inj} = 22.5$ ms.
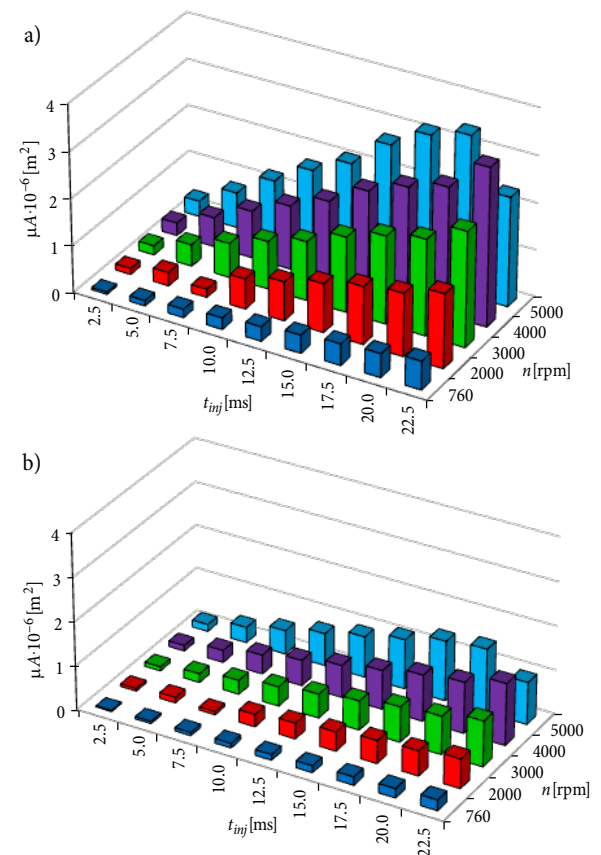

Fig. 9. Calculated injector conductance for section I:
a – without nozzles; b – with the nozzles fitted

Table 4. Conductance for section I for both test runs

t_{inj} [ms]	Conductance 10^{-6} [m^2]									
	without nozzles					with nozzles				
	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]
2.5	0.047609	0.127247	0.197172	0.273226	0.333306	0.023500	0.060730	0.093884	0.128093	0.159231
5.0	0.113424	0.287952	0.462756	0.629071	0.752695	0.049828	0.128300	0.201592	0.277245	0.352843
7.5	0.178535	0.178537	0.734768	1.008576	1.250707	0.072612	0.072612	0.317631	0.435602	0.539982
10.0	0.245851	0.644908	1.021846	1.362232	1.713996	0.101119	0.283227	0.440720	0.581031	0.736587
12.5	0.310284	0.832632	1.261192	1.700889	2.095205	0.129356	0.360883	0.546588	0.733180	0.930370
15.0	0.388083	1.042261	1.603278	2.160366	2.727228	0.155476	0.437894	0.663947	0.887442	1.127562
17.5	0.458298	1.232657	1.869067	2.479200	3.165938	0.186829	0.521442	0.804412	1.053554	1.359005
20.0	0.508923	1.339412	2.045623	2.718006	3.392856	0.208896	0.570297	0.868615	1.161002	1.447734
22.5	0.606423	1.582165	2.454287	3.368279	2.331105	0.242382	0.671260	1.037129	1.408142	0.960226

The pulsator was responsible for the fuel dosage issues in both cases. In the first case, it reacted in an unstable way for the given parameters and in the second one – the opening time significantly deviated from the conditions of normal operation but it was recognized as important in the learning objectives.

It should be noted that the throughput values are averaged in the course of the research being the resultant of both the time when the injector is open and the time when the injector is closed. Knowing the duration when the injector is open, we may describe the conductance of the opening. However, in this case, average-cycle conductance was applied describing the flow capability of the research objects in variable conditions of input parameters (injector opening time and operation frequency).

The determined uneven injector dosage described by Eq. (8) is distributed similarly in both cases (Fig. 10). Average dosage unevenness of the system without nozzles was 1.3667%, and with the nozzles fitted – 1.4086% (Table 5).

The average difference in the unevenness was 0.0419% (Fig. 11). The minimum value was 0.0694%, and the maximum – 0.8803% (Table 6).

The difference in the unevenness seems to have a small value in accordance to the correction capability of the oxygen sensor (0.5%). It must be noted, however, that contamination of the nozzle or improper boring significantly affect the said unevenness. The points in which the unevenness difference exceeds 0.5% are conspicuous, which can be a reason for the air-fuel ratio interference in the injector opening time control.

Qualitatively assessing the identification, it has to be stated that the average error (Fig. 12) oscillated around 3000 Pa for the empty container and 1500 Pa for the filled containers. It is (1.5% and 0.75%) of the tested range.

The maximum error (Fig. 13) has a limit value of 8500 Pa for the empty container, and the minimum error is ca. 1500 Pa for the filled containers. It is (4.2% and 0.75%) of the studied range.
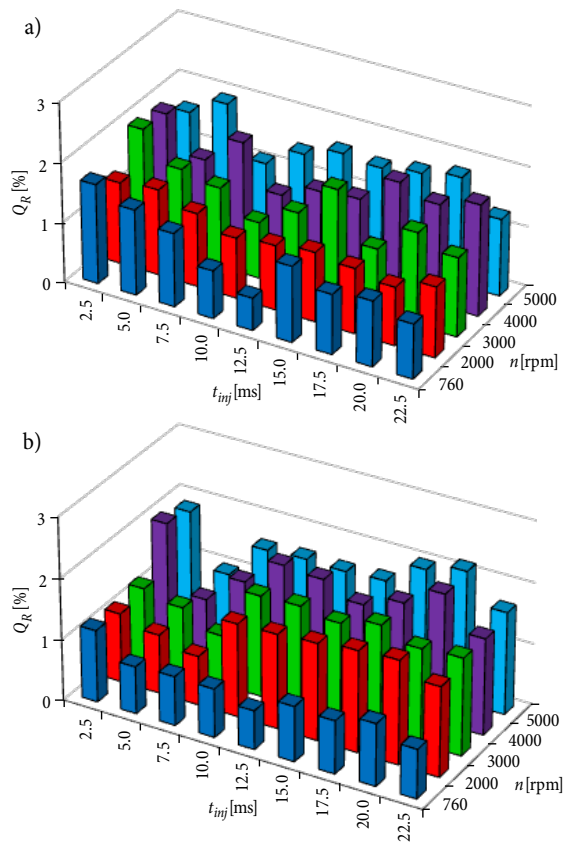

Fig. 10. Calculated uneven injector dosage: a – without nozzles; b – with the nozzles fitted

The determination coefficient (Fig. 14) oscillated around 98.50% for the empty container and 99.50% for the filled containers.

Summing up the qualitative analysis, we need to state that in none of the cases was the deviation above 5% of the studied range observed, which can be deemed as a very good result.

The flow characteristics are close to linear (Fig. 15). Two deviating points were observed resulting from the operation of the actuation system.

Table 5. Unevenness of the injector dosage

t_{inj} [ms]	Uneven injector dosage Q_R [%]									
	without nozzles					with nozzles				
	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]
2.5	1.667713	1.371088	1.950818	1.894666	1.606191	1.181191	1.13082	1.224446	1.988224	1.872186
5.0	1.433119	1.440550	1.462469	1.299216	1.929087	0.774917	0.967786	1.095294	0.905241	1.004571
7.5	1.231836	1.231858	1.33439	1.773119	1.099377	0.806981	0.806971	0.819242	1.385511	1.593981
10.0	0.801750	1.013234	0.940431	1.075269	1.443699	0.798383	1.530112	1.661549	1.845609	1.627213
12.5	0.542777	1.080799	1.295604	1.324820	1.640327	0.637300	1.550260	1.683338	1.797535	1.607062
15.0	1.269747	1.161856	1.874251	1.386416	1.582451	0.905537	1.593211	1.592408	1.569643	1.637448
17.5	1.001894	1.091333	1.075514	1.854671	1.680616	0.870455	1.668933	1.751504	1.783564	2.008668
20.0	1.092339	0.976003	1.541046	1.673878	1.796623	1.022959	1.706936	1.557852	2.116653	2.162899
22.5	0.913265	1.178476	1.319372	1.859688	1.287648	0.808280	1.475920	1.599671	1.580091	1.678223

Table 6. Difference in the uneven injector dosage

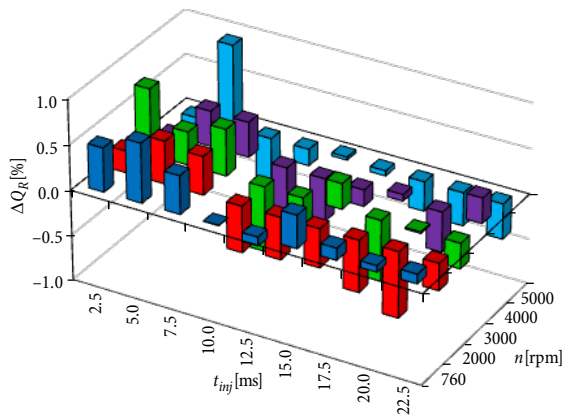| t_{inj} [ms]	Difference in the uneven injector dosage ΔQ_R [%]				
	760 [rpm]	2000 [rpm]	3000 [rpm]	4000 [rpm]	5000 [rpm]
2.5	0.486522	0.240267	0.726372	−0.093558	−0.265995
5.0	0.658202	0.472763	0.367175	0.393976	0.924516
7.5	0.424855	0.424888	0.515148	0.387608	−0.494604
10.0	0.003367	−0.516878	−0.721118	−0.770340	−0.183514
12.5	−0.094523	−0.469462	−0.387735	−0.472715	0.033266
15.0	0.364210	−0.431355	0.281843	−0.183227	−0.054997
17.5	0.131439	−0.577601	−0.675990	0.071107	−0.328052
20.0	0.069380	−0.730932	−0.016805	−0.442775	−0.366276
22.5	0.104985	−0.297443	−0.280299	0.279598	−0.390575

Fig. 11. Difference in the uneven injector dosage
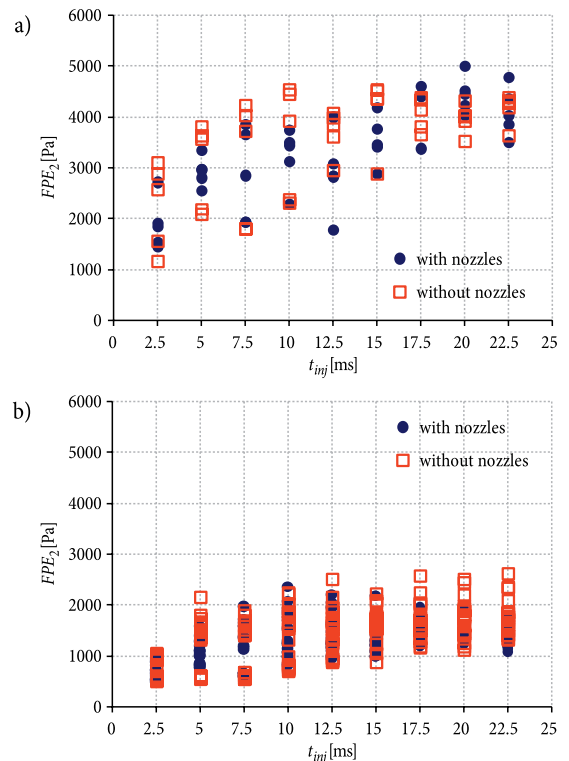
Fig. 12. Average error of identification for: a – the empty container; b – the filled containers
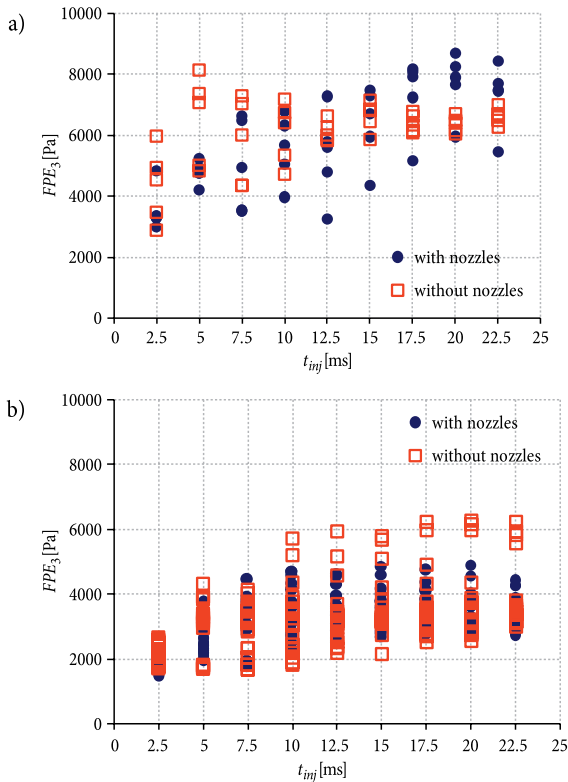
Fig. 13. Maximum error of identification for: a – the empty container; b – the filled containers
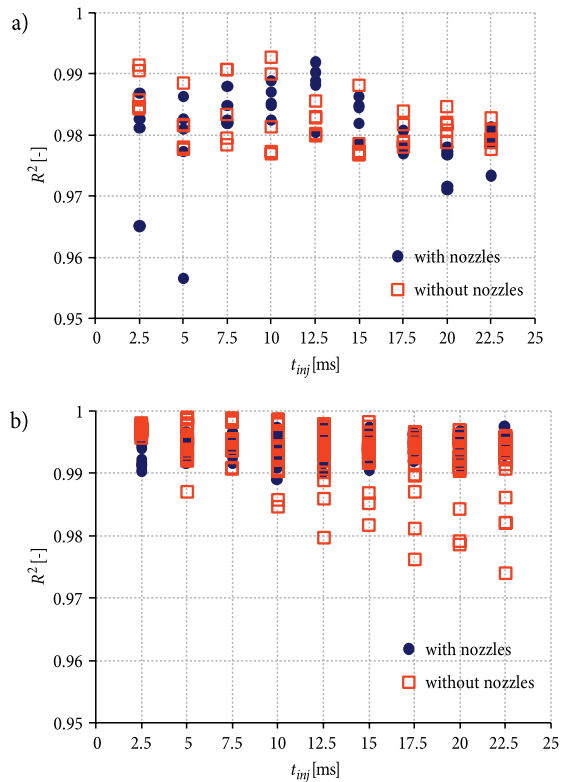

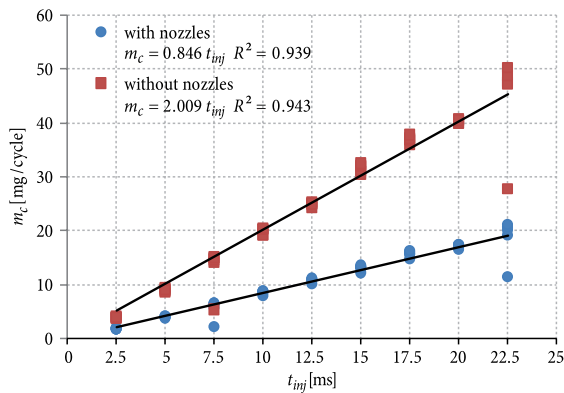Fig. 14. Determination coefficient for: a – the empty container; b – the filled containers

Fig. 15. Flow characteristics of the studied system

Conclusions

The presented research methodology connected with the original stand provides an opportunity of determining the flow characteristics of the LPG/CNG injectors. The essence is the fact that the research is conducted under dynamic conditions, which provides the possibility of deeper functional analysis that is closer to typical operating conditions. The unevenness of the feed is believed to be the cause of operational problems of engines fitted with alternative fuel systems. From the research, the following conclusions were drawn:

– The determined averaged throughputs fall in the range of (0.0235…3.3683) mm^2 for the studied object.
– The flow characteristics are close to linear (Fig. 15). Two deviating points were observed

resulting from the operation of the actuation system.
– The average uneven feed of the system without nozzles was 1.3667%, and with the nozzles fitted – 1.4086%. The difference is 0.0419%. The minimum value is 0.0694, and the maximum – 0.7703, which may influence the correction of the combustible mixture composition made through an oxygen sensor.
– During qualitative analysis of the identification, it was observed that the average error did not exceed 1.5% and the maximum error did not exceed 4.2% of the studied range. The determination coefficient oscillated around 99%.

The necessity of monitoring of the LPG injector uneven dosage was confirmed during maintenance and for cases when new components with individually bored nozzles are fitted.

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