POSSIBILITY OF USING PRESSURE TIMING COURSE FROM OUTLET NOZZLE OF LOW-PRESSURE IMPULSE GAS-PHASE INJECTOR TO EVALUATE ITS FLOW PROPERTIES

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Abstract. The continuous tightening of emission standards in the approval process of internal combustion engines of vehicles used in transport entails changes in the organization of the combustion process, as well as a necessity of searching for alternative fuels. The alternative fuels that are most common in this area are LPG (liquefied petroleum gas) and CNG (compressed natural gas). One of the most popular gas systems on the EU market is LPG vapour phase injection with the use of a low-pressure impulse gas injector. Its popularity is attributed to the fact that it is universal and allows for simple conversion in SI (spark ignition) engines. Uncomplicated and low-cost research methods for determining the flow characteristics of gas injectors are continuously being looked for. The paper presents the results of plunger gas injector research. For this purpose, an original test stand was used, which enables recording pressure courses from the injector outlet nozzle using a custom sensor. The sensor, in combination with oscilloscope, allows for recording pressure courses in a cycle of one opening of an order of few milliseconds. The surface area located under the pressure course was specified as pressure timing (PT). The variability of PT with respect to the length of the injector opening control pulse provides information about the flow characteristics. In order to verify the adopted research methodology, a flow meter was used, which determined the flow value at full/continuous opening, as well as during impulse operation. The obtained differences of both methods are minor with respect to the maximum flow value of the tested injector; therefore, the proposed method should be considered correct. An undoubted disadvantage of the adopted method is the necessity of having information on the flow value at full opening of the injector, as it is the reference point in the calculations.

Keywords: mechanical engineering, gas injector, research.

Introduction

The trend of alternative fuels is noticeable in Europe. This is due to successive legislation on CO_2 emissions [1; 2]. There are works on using alternative fuels in transport, especially those with lower carbon content in relation to commonly used fuels [3-5], as well as different organization of the combustion process is proposed [6-8]. From 2020, CO_2 emissions during vehicle type approval can be 95 $g \cdot km^{-1}$, 15% reduction by 2025 and 37.5% reduction by 2030 [9]. Ultimately, the propulsion sources are likely to be electric motors and hybrid assemblies with varying use of the internal combustion engine [10-12]. There is also growing interest in the use of alternative fuels in machinery and off-road vehicles [13; 14].

New methods are also being sought to provide a functional evaluation of the components of alternative power systems. The pulse low-pressure gas-phase injector is the component responsible for fuel delivery to the engine intake manifold. The commonly used magnetic actuators [15] are trying to be replaced by piezoelectric ones [16; 17].

The knowledge of the flow characteristics of the gas injector is fundamental in the organization of the power process and the conversion of the engine to alternative power. The flow characteristics can be determined computationally using analytical models [18] or computational fluid dynamics (CFD) [19; 20]. Experimental determination of flow characteristics of gas injectors commonly uses a flow meter [21] and sometimes tank methods [22].

The purpose of this study was to evaluate the applicability of an innovative method for determining flow characteristics using a pressure sensor that reads the outlet pressure of a nozzle outlet. The area falling under the pressure waveform was defined as pressure timing. By cycling the injector with different opening times, the degree of fill contained in the pressure timing could be calculated relative to the total. With the degree of filling and the maximum volumetric flow rate available, it was possible to determine the injector flow rate.

Materials and methods

The tests were carried out on a Valtek Rail Type 30 plunger injector (Fig. 1). This injector is a low-pressure impulse gas-phase injector. In the idle state, without power, the piston 1 presses the seat in the corps 3 by means of the spring 2. When power is applied, the electomagnetic field generated within the coil 5 moves the plunger 1 into the pilot 7 allowing gas to flow from the inlet nozzle 8 to the outlet nozzle 9.The basic technical data of the Valtek Rail Type 30 injector are presented in Table 1.

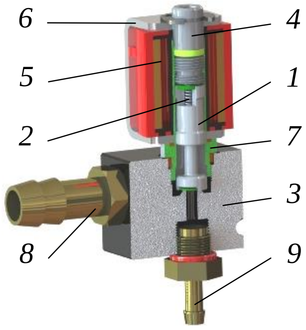

Fig. 1. **Valtek Rail Typ 30 gas injector:** 1 – plunger; 2 – spring; 3 – corps; 4 – limiter; 5 – coil; 6 – electromagnetic circuit jumper; 7 – pilot; 8 – inlet nozzle; 9 – outlet nozzle [24]

Table 1

Basic technical dataof the Valtek Rail Typ 30 gas injector [23]

Parameter	Unit	Value
Coil resistance	Ω	3
Plunger displacement	m	$0.4 \cdot 10^{-3}$
Nozzle size	m	$(1.5…3.5) \cdot 10^{-3}$
Oopening time	s	$3.3 \cdot 10^{-3}$
Closing time	s	$2.2 \cdot 10^{-3}$
Max working pressure	Pa	$4.5 \cdot 10^{5}$
Operating temperature	K	(–20…120) + 273.15
Operating voltage range	VDC	12

The test stand (Fig. 2) is used to determine the flow parameters and fuel dosage non-repeatability of low-pressure gas-phase injectors [25]. For safety reasons, the tests were conducted using air instead of gas. First, the air from the air supply with the air preparation system 1 flows to the buffer tank 2. Then, the flow rate is measured using the flow meter 3. In this case, the flow rate value is averaged due to the pulse operation of the injector 4 performed by the pulse generator 5 (based STAG LLC ECU). A special pressure sensor 6 is mounted to the outlet of the nozzle injector 4, which measures pressure pulses during cyclic opening of the injector. The principle of operation and measurement capabilities of the sensor 6 are described in detail [25].

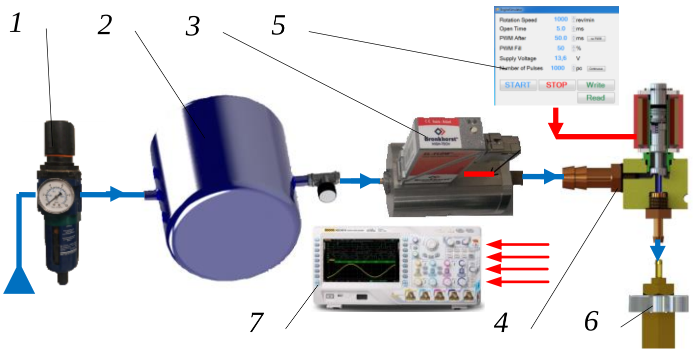

Fig. 2. **Structural schematics of the test stand:** 1 – air supply with air preparation system; 2 – buffer tank; 3 – flow meter; 4 – tested injector; 5 – pulse generator; 6 – pressure gauge; 7 – oscilloscope

Parameters of the measurement equipment are presented in Table 2.

The pressure waveform at the injector nozzle shows its cyclic opening. Fig. 3 shows an example of the pressure waveform at the injector nozzle exit for five consecutive cycles at the opening excitation frequency $f = 1000$ imp·min^{-1} and the duration of the excitation pulse $t_{inj} = 5 \cdot 10^{-3}$ s. During $f = 1000$ imp·min^{-1} time of single cycle is $t_{inj} = 60 \cdot 10^{-3}$ s. In Fig. 4 one cycle is shown for the opening (red line) and the reference run (green line). The reference in this case is the theoretical assumption of maximum $Q_{\max}$ in relation to $p_{\max}$ in cycle t_{imp} in which the injector would be continuously open.

Table 2

Parameters of the measurement equipment

Parameter	Measurement device	Response time	Range (Accuracy)
Pressure	MPXH6400A	$< 1 \cdot 10^{-3}$ s	$(20\ldots400) \cdot 10^{3}$ Pa (±0.25%)
Flow	BRONKHORST F-113AC-M50	< 2 s	$(0\ldots500)$ l_n·min^{-1} (±0.5%)
Record	RIGOL MSO4014	bandwidth – 100 MHz; sample rate – 4 GS·s^{-1}	

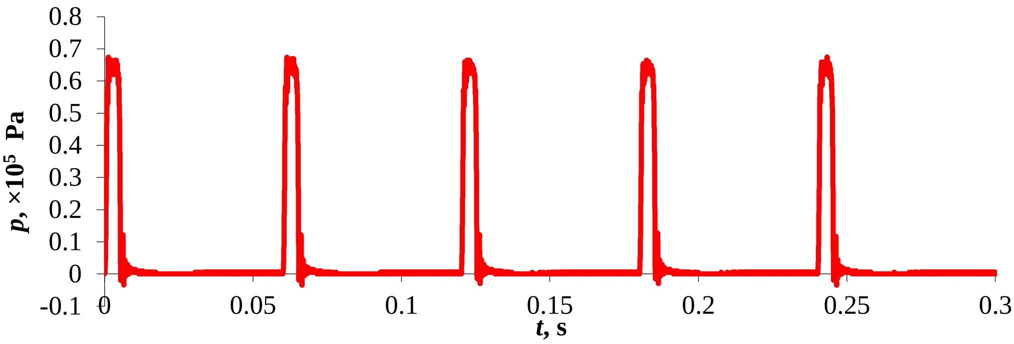

Fig. 3. **Example pressure waveform for five cycles:** $f = 1000$ imp·min^{-1}; $t_{inj} = 5 \cdot 10^{-3}$ s

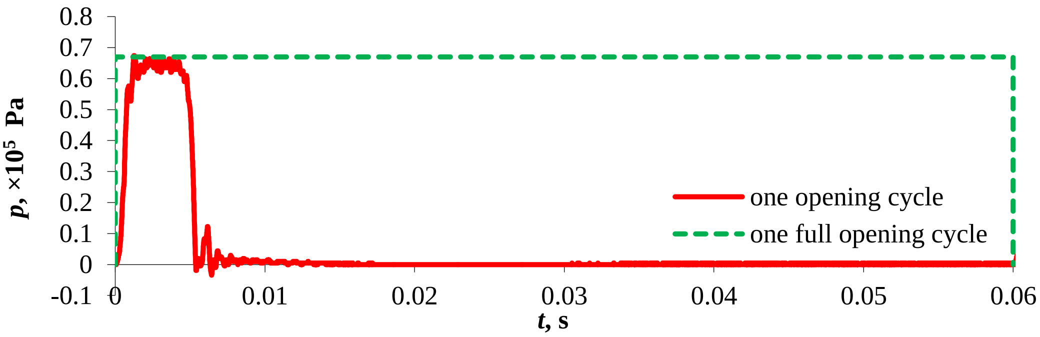

Fig. 4. **Example pressure waveform for one cycle:** $f = 1000$ imp·min^{-1}; $t_{inj} = 5 \cdot 10^{-3}$ s

Based on a single opening run, the area under the line $p(t)$ can be computed resulting in the pressure timing (PT) described by Eq. 1.

$$PT = \int_{0}^{t_{cycle}} p(t)\,\mathrm{d}t\,, \tag{1}$$

where $p(t)$ – pressure, Pa;
t – time, s;
t_{cycle} – cycle duration, s.

PT values were calculated using the rectangular method. In each case, the time step of pressure recording was $1 \cdot 10^{-5}$ s. The reference representing the cycle of one full opening was $PT_{\max}$ described by Eq. 2:

$$PT_{\max} = p_{\max} t_{cycle}\,, \tag{2}$$

where $p_{\max}$ – maximum pressure, Pa;

With maximum volumetric flow rate (Q_{max}) the volumetric flow rate was calculated at specific opening times (Eq. 3):

$$Q = \frac{PT}{PT_{max}} Q_{max} = \zeta Q_{max} . \quad (3)$$

Results and discussion

To determine PT at each opening time t_{inj}, 5 consecutive pressure cycles at a frequency of 1000 imp·min^{-1} were used. The cycles were divided into 5 separate cycles for which PT was determined. The result was then related to the PT_{max} and the coefficient ζ was calculated. As a result, the volumetric flow rate (Q) was obtained having Q_{max} = 100 l_n·min^{-1} [24]. The range of injection times was within the following limits (3…15)·10^{-3} s. In Fig. 5a the flow characteristic of tested injector is presented. It was determined on the basis of average values of PT with marked whiskers representing scatter from 5 measurements. The characteristic was approximated by a straight line (R^2 = 0.991). Lower growth rates have reported Q in longer opening timings t_{inj} resulting from pressure fluctuations in the opening time range in cyclic operation. This is also confirmed by the positive value of the free expression of the function [26].

Having the volumetric flow rate determined from PT, a comparative study was conducted using a flow meter. The result represented the average value from the cycle (opening-closing). As in the previous case, the measurement was repeated 5 times with an interval of 5 s. Verification showed some similarity of the obtained characteristics (Fig. 5b). The flow characteristic obtained with the flow meter is more linear (R^2 = 0.999) and this time the value of the free expression of the function is negative, according to [26]. The directional coefficients show some discrepancies (about 12%), but based on the verification, it can be concluded that the method proposed in the paper for determining Q from PT is correct but needs further refinement. The discrepancy revealed by longer opening times is probably due to PT_{max} determined on the basis of p_{max}. In a further stage, work will be carried out to designate p_{max} for each cycle based on the averaged pressure value at full open time.

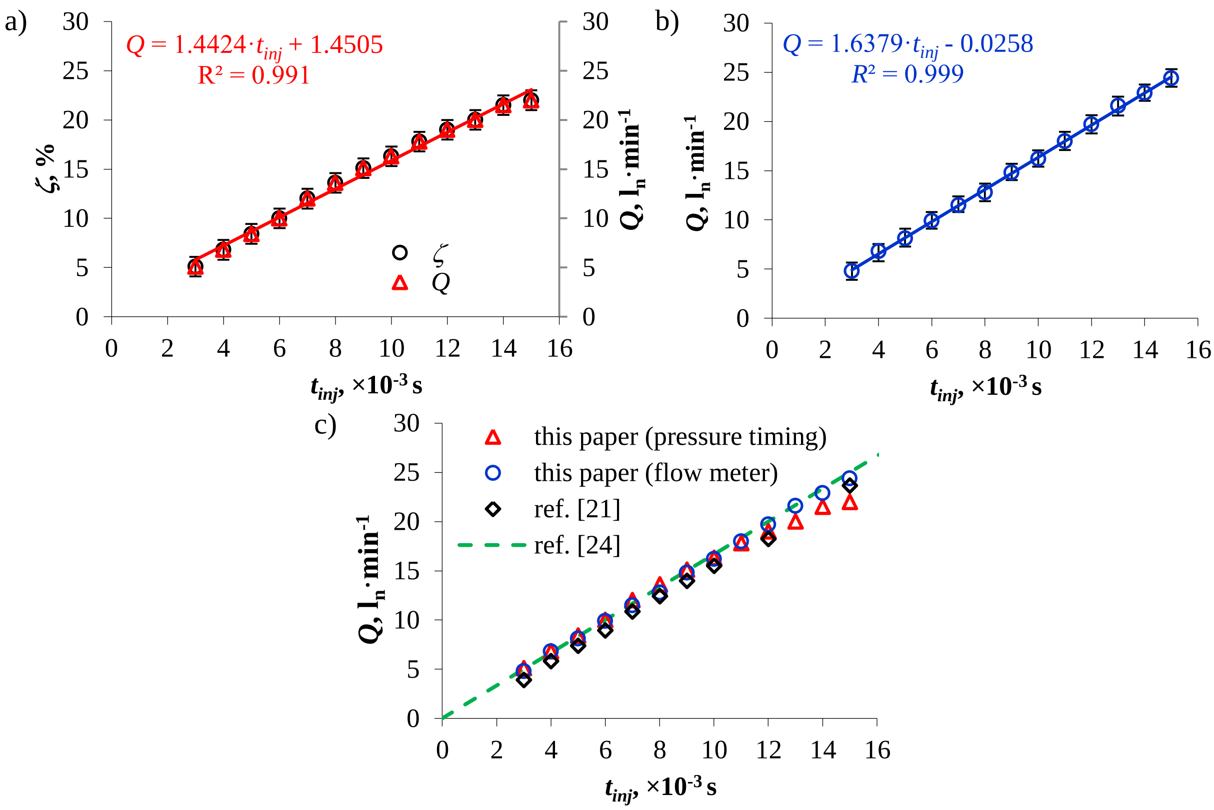

Fig. 5. **Flow characteristics:** a – on the basis of pressure timing (PT); b – using a flow meter; c – comparison with literature reports

In the final step, the test results were compared with literature reports. In [21] the output of Valtek Rail Type 30 gas injector was presented as the mass of air per cycle. Given the air density at normal conditions of 1.29 $kg \cdot m^{-3}$ and a pulse frequency of 1000 $imp \cdot min^{-1}$, it was possible to calculate the volumetric flow rate. In addition, a line representing the theoretical value of the flow rate was drawn, i.e. at $t_{inj} = 0 \cdot 10^{-3}$ s the value $Q = 0$ $l_n \cdot min^{-1}$, in contrast, at $t_{inj} = 60 \cdot 10^{-3}$ s, the flow rate reaches its maximum value $Q_{max} = 100$ $l_n \cdot min^{-1}$ [24]. Analysing the summary of flow characteristics (Fig. 5c) one can see their similarity. Even the theoretical characteristics assuming the intersection of the approximating function at 0.0 shows discrepancies only in the range of shorter injector opening times. The biggest difference was observed for Q determined from PT at the maximum opening time of $15 \cdot 10^{-3}$ s. Pressure fluctuations at full injector opening can be considered as the reason for this, as mentioned earlier.

Conclusions

1. An original method is presented, which allows the flow characteristics to be determined using the pressure waveform at the outlet of the injector nozzle.
2. In determining the volumetric flow rate, the pressure timing (PT) values were used, which were related to PT_{max} with the injector constantly open.
3. Comparing the flow characteristics obtained from the pressure timing and flow meter, there were about 12% discrepancies in the values of directional coefficients and small differences in the values of free expressions of the describing function.
4. The reference of flow characteristics determined in the course of the research to the results presented in literature reports showed the similarity, except for the range of longer opening times, which is probably caused by pressure fluctuations in the range of full opening of the injector.
5. In the further step, determination of the pressure timing for each cycle based on the averaged value of the pressure at the time of full opening is provided.

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