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The fuel jet divergence angle in the Fiat MultiJet engine

INTRODUCTION

A lot of research on developing and improving the combustion process is being conducted worldwide [1, 2, 3, 5, 6, 13]. The process of combustion in self-ignition engines depends significantly on the dynamics and pattern of the fuel jet and the fuel physicochemical properties [4, 12, 16]. One of the major parameters defining the shape of the sprayed fuel jet is its divergence angle. The divergence angle of the jet is determined by its outer shape. The exact determination of the jet divergence angle is only possible when the stream is injected into vacuum. During injection into a cylinder, a jet contraction contraction occurs, which is associated with the action of aerodynamic medium resisting forces. The determination of the jet divergence angle and the knowledge of its extent enables the determination of the jet field using the jet surface area. The jet divergence angle is influenced by many factors, which undergo constant changes during the process of injection [11]. One of the most important parameters influencing the magnitude of the jet divergence angle is the injection pressure. The increase in injection pressure causes an increase in the velocity of fuel discharge from the sprayer, which in turn has the effect of increasing its range and turbulence. Intensifying the jet turbulence results in fuel droplets being carried over in the radial jet direction. This increases the head resistance of the jet, which is made up of finer droplets. Therefore, the jet divergence angle increases, while the jet range decreases. This phenomenon is advantageous, because the injected fuel will not reach the cylinder liner walls or the piston, which would otherwise result in an increase in the quantity of fuel evaporated from the walls. It is therefore essential that the injection pressure is not too high, since in that case an increased quantity of fuel would get to the combustion chamber walls. One of the ways of avoiding this phenomenon is by increasing the number of sprayer nozzles. This will reduce the overall velocity of fuel outflow from the sprayer nozzles. In addition, a larger number of nozzles will enable a better mixing of the fuel with the air. However, when increasing the number of sprayer nozzles it should be borne in mind that the total diameter of all sprayer nozzles must remain unchanged. By increasing the number of sprayer nozzles, while retaining the same diameter, a considerable increase in fuel consumption may be caused. Reducing the sprayer nozzle diameter, in turn, results in an increase in fuel discharge from the sprayer, thus influencing the jet divergence angle. Therefore, when designing the combustion chamber it is essential to correctly select the injection pressure and the number and diameter of sprayer nozzles. Aside from the injection pressure, another parameter influencing the jet convergence angle is the pressure prevailing in the cylinder during the fuel injection process. The increase in the difference between the injection pressure and the pressure prevailing in the cylinder results in a reduction in fuel discharge velocity. The jet divergence angle is also significantly influenced by the physicochemical properties of the fuel, such as density, viscosity and surface tension [12]. According to reference [9], the greatest effect on the jet divergence angle is exerted by viscosity. The study referred to above has found that with the increase in viscosity the jet divergence angle decreases. Higher viscosity makes breaking up droplets into smaller-diameter droplets more difficult. Larger droplet diameters and greater jet integrity favour the reduction of the aerodynamic resistance of the medium. Excessively high fuel viscosity adversely affects the atomization of the fuel. This effect can be eliminated by raising the fuel temperature. This will cause a greater size reduction of the droplets, whereby the jet divergence angle will rise and the area of heat exchange between the droplets and the air-fuel mixture in the cylinder will increase. The fuel jet divergence angle is one of the most important factors determining the quality of fuel atomization. The

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jet range and the mean droplet diameter are closely related to the jet divergence angle. These parameters have a significant effect on the process of formation of the air-fuel mixture and its combustion. The jet divergence angle strongly influences the fineness of fuel atomization, fuel vaporization rate and fuel diffusion to the air contained in the cylinder. The rate of heat release in the engine during the combustion process depends primarily on the quality of the air-fuel mixture formed.

1. THE ANGLE OF DIVERGENCE OF THE JET OF FUEL INJECTED INTO THE CYLINDER

The dynamics of propagation of the atomized fuel jet is defined by, among others, the jet divergence angle. Due to the complexity of the dynamics and pattern of a nonstationary fuel jet in the operation conditions of a self-ignition engine, all existing empirical relationships are developed based on experimental testing results. The mean volume-surface area droplet diameters have been determined in the paper according to selected empirical relationships:

– developed by Kuleshov and Mahkamov [14]:

$$\theta_{Kuleshov} = 2 \cdot \mathrm{arctg}(F \cdot We^{0.32} \cdot M^{-0.07} \cdot E^{-0.12} \cdot \rho^{0.5}) \tag{1}$$

where:
F – empirical constant which, according to [14], is equal to 0.0075÷0.009
We – Weber number,
M – M criterion, which describes the relationship between surface tension forces, inertia and viscosity,
E – E number, which defines the nonstationarity criterion for the process of fuel discharge from the sprayer,
ρ – ratio of air to fuel density.

Studies [7, 8] have provided relationships for the determination of criterial numbers, namely the Weber (We) number, the M criterion, the E number and the ρ number.

– developed by Sitkei [17]:

$$\theta_{Sitkei} = 0.3 \cdot \left(\frac{l_o}{d_o}\right)^{-0.3} \cdot \left(\frac{\rho_G}{\rho_L}\right)^{0.1} \cdot \left(\frac{U \cdot d_o \cdot \rho_L}{\eta_L}\right)^{0.7} \tag{2}$$

where:
l_o – sprayer nozzle channel length,
d_o – sprayer nozzle diameter,
ρ_G – density of the medium (gas) into which the fuel is injected,
ρ_L – fuel density,
η_L – fuel dynamic viscosity,
U – the velocity of fuel discharge from the sprayer, as determined based on the Bernoulli theory:

$$U = \frac{\sqrt{2 \cdot (p_{inj} - p_c)}}{\rho_L} \tag{3}$$

where:
p_{inj} – fuel injection pressure,
p_c – cylinder pressure.

– developed by Reitz and Bracco [18]:

$$\theta_{Reitz} = 2 \cdot \mathrm{arctg}\left(\frac{4\pi}{A} \cdot \sqrt{\frac{\rho_G}{\rho_L}} \cdot f\left[\frac{\rho_G}{\rho_L} \cdot \left(\frac{Re}{We}\right)^2\right]\right) \tag{4}$$

where:
Re – Reynolds number.
A – constant which is determined from the following relationship:

$$A \approx 3 \cdot \frac{l_o}{3.6 \cdot d_o} \tag{5}$$

– developed Hiroyasu and Arai [10]:

$$\theta_{Hiroyasu} = 83.5 \cdot \left(\frac{l_o}{d_o}\right)^{-0.22} \cdot \left(\frac{d_o}{d_s}\right)^{0.15} \cdot \left(\frac{\rho_G}{\rho_L}\right)^{0.26} \quad (6)$$

where:
d_s – sprayer well diameter.

– developed by Naber and Siebers [15]:

$$\theta_{Naber} = 2 \cdot \mathrm{arctg}\left[\alpha \cdot \left(\frac{\rho_G}{\rho_L}\right)^{0.19}\right] \quad (7)$$

α – empirical constant which, according to [15], equals 0.31÷0.40.

A common feature of empirical formulae 1, 2 4÷7, which enable the calculation of the jet divergence angle, is that all of them allow for the density of fuel injected to the cylinder and the density of air contained in the cylinder.

2. THE OBJECT OF INVESTIGATION AND CONTROL AND MEASURING APPARATUS

Tests were carried out on an engine dynamometer test stand including a FIAT MultiJet 1.3 SDE 90 KM engine. The feed system of the test engine was equipped with the common rail system and electromagnetic fuel injectors with six-nozzle sprayers, each with a spraying nozzle diameter of 0.12 mm. During the tests, the engine was running following the load characteristics at n=1750 rpm and n=4000 rpm, respectively. The basic technical specification of the test engine is given in Table 1.

Tab. 1. The engine specification

Parameter	Unit	Value
Cylinder arrangement	-	in-line
Number of cylinders	-	4
Type of injection	-	direct, multi-stage fuel injection
Compression ratio	-	17,6
Cylinder bore	mm	69,6
Piston stroke	mm	82
Engine cubic capacity	cm^3	1251
Maximum engine power	kW	66
Maximum power rotational speed	rpm	4000
Maximum torque	N·m	200
Maximum torque rotational speed	rpm	1750

Figure 1 shows a block diagram of a system for the measurement of: cylinder pressure variation, injection line pressure variation, injector operation control current variation, and crankshaft rotation angle variation.

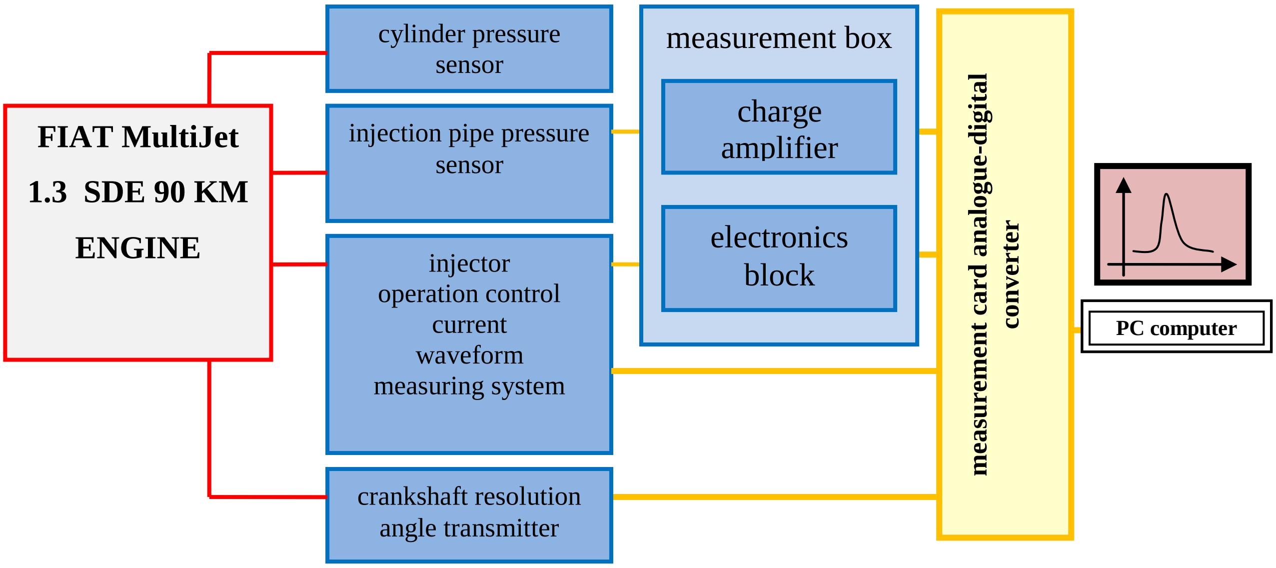

Fig. 1. Block diagram of the internal combustion engine fast-variable quantity measuring system

The measuring system consists of an AVL GH13G type piezoelectric sensor for measuring the combustion pressure in the cylinder; a sensor for measuring the injection line pressure; a system for measuring the injector operation control current waveform, a charge amplifier and a crankshaft rotation angle encoder. The fuel consumption was measured using an AVL 730 fuel dosimeter.

3. MEASUREMENT RESULTS AND THEIR ANALYSIS

In making the analysis of the testing results for the engine running according to the load characteristics at n=1750 rpm and n=4000 rpm, respectively, the jet divergence angle θ was determined from relationships 1, 2, 4, 6÷7, which are presented in Tables 2 and 3, respectively.

Tab. 2. The jet divergence angle θ for the engine running according to the load characteristics at n=1750 rpm

Moment obrotowy, N·m	P_{inj}, MPa	$\Theta_{Kuleshov}$, °	Θ_{Sitkei}, °	Θ_{Reitz}, °	$\Theta_{Hiroyasu}$, °	Θ_{Naber}, °
10	41,8	4,5	13,0	14,0	14,2	17,1
20	46,0	5,6	13,5	14,3	14,3	17,2
30	50,4	6,2	14,1	14,7	14,5	17,4
40	56,0	7,5	14,8	15,8	15,1	17,9
50	62,1	8,5	15,6	16,6	15,5	18,2
60	67,3	9,5	16,1	17,2	15,8	18,5
70	76,3	10,8	17,0	17,9	16,1	18,7
80	82,1	10,1	17,5	18,4	16,3	18,9
90	85,1	11,1	17,9	19,3	16,8	19,3
100	86,3	12,3	18,1	20,3	17,2	19,7
110	89,1	13,6	18,5	21,3	17,7	20,0
120	88,1	14,5	18,6	22,0	18,0	20,3
130	89,7	11,9	17,7	17,4	15,9	18,6
140	88,9	12,1	17,7	17,4	15,8	18,5
150	88,9	12,7	17,7	17,8	16,1	18,7
160	89,9	13,3	17,9	18,2	16,2	18,9
170	90,3	13,7	17,9	18,4	16,3	18,9
180	89,7	14,3	17,9	18,6	16,4	19,0
190	90,3	14,8	18,0	18,9	16,6	19,1
202	90,1	15,1	18,0	19,1	16,7	19,2

Tab. 3. The jet divergence angle θ for the engine running according to the load characteristics at n=4000 rpm

Moment obrotowy, N·m	P_{inj}, MPa	$\Theta_{Kuleshov}$, °	Θ_{Sitkei}, °	Θ_{Reitz}, °	$\Theta_{Hiroyasu}$, °	Θ_{Naber}, °
10	83,9	6,2	17,3	15,8	15,1	17,9
20	87,7	6,7	17,6	16,0	15,2	18,0
30	93,7	7,5	18,1	16,2	15,3	18,0
40	98,7	7,9	18,7	17,4	15,9	18,5
50	103,3	7,6	18,9	16,5	15,4	18,2
60	109,3	8,3	19,3	16,8	15,6	18,3
70	114,1	8,7	19,6	16,8	15,6	18,3
80	122,1	9,2	20,2	17,4	15,8	18,5
90	129,3	10,0	20,7	17,7	16,0	18,7
100	137,5	10,5	21,3	18,0	16,2	18,8
110	148,7	11,0	21,9	18,3	16,3	18,9
120	151,3	14,7	22,0	18,6	16,5	19,0
130	159,3	15,3	22,5	18,8	16,5	19,1
140	158,7	16,0	22,5	18,9	16,6	19,2
150	159,3	16,4	22,5	19,0	16,6	19,2
158	158,3	16,5	22,5	19,0	16,6	19,2

For the engine running following the load characteristics at a rotational speed of n=1750 rpm, the injection line pressure ranged from 41.8 MPa to 90.3 MPa. For the engine running according to the load characteristics at a rotational speed of n=4000 rpm, the injection line pressure ranged from 83.9 MPa to 159.3 MPa.

The smallest jet divergence angle θ was obtained when calculating it from the relationship provided by Kuleshov and Mahkamov. For the engine running according to the load characteristics at n=1750 rpm, the jet divergence angle ranged from 4.5° to 15.1°, while at n=4000 rpm, from 6.2° do 16.5°. The largest jet divergence angle θ was obtained by calculating it from the relationship provided by Naber and Siebers. For the engine running according to the load characteristics at n=1750 rpm, the jet divergence angle ranged from 17.1° to 19.2°, while at n=4000 rpm, from 17.9° to 19.2°. The relationships given by Kuleshov and Mahkamov and by Naber and Siebers, as compared to the remaining formulae, did not allow for the length of the sprayer nozzle channel. The Naber and Siebers relationship considers only the change in the fuel density and the density of the medium to which the fuel is injected.

The trend in the behaviour of the jet divergence angle as determined using relationships 1, 2, 4, 6÷7 is similar.

CONCLUSIONS

From the results of the performed investigation and their analysis, the following conclusions can be drawn:

– for the engine running following the load characteristics at n=1750 rpm, the pressure in the injection line increased from 41.8 MPa to approx. 90.3 MPa, and upon reaching the load of M_o=110 N·m, the injection line pressure stabilized at a level of 88.9÷90.3 MPa;
– for the engine running following the load characteristics at n=4000 rpm, the pressure in the injection line increased from 83.9 MPa to approx. 159.3 MPa, and upon reaching the load of M_o=130 N·m, the injection line pressure stabilized at a level of 158.3÷159.3 MPa;
– the relationship developed by Naber and Siebers, as the only one, considers only the fuel density and the cylinder air density in the calculation of the jet divergence angle;
– the relationships provided by Kuleshov and Mahkamov, Sitkei, Reitz and Bracco, Hiroyasu i Arai, all consider the sprayer nozzle diameter in jet divergence angle calculation;

– the empirical formulae proposed by Kuleshov and Mahkamov and by Sitkei all allow for the differences between the injection line pressure and the cylinder pressure.

To sum up, it can be concluded that the trend in the behaviour of jet divergence angle value variations for the relationships discussed is similar.

Abstract

The paper provides empirical formulae that enable the determination of the divergence angle of the injected fuel jet. Tests were carried out on a dynamometer test stand equipped with a FIAT MultiJet 1.3 SDE 90 KM engine, which ran following the load characteristics at a crankshaft rotational speed of 1750 rpm and 4000 rpm, respectively. During testing, the engine was fed with commercial diesel oil. Moreover, the test stand was furnished with a system for measuring fast-variable quantities, i.e. cylinder pressure, injection line pressure and the injector operation control current waveform. In addition, the torque was measured. Based on the tests carried out on the dynamometer test stand and from the empirical formulae developed by Kuleshov and Mahkamov, Sitkei, Reitz and Bracco and Hiroyasu, and Arai, the jet divergence angle was determined.

Keywords: combustion engine, parameters of the fuel spray, spray cone angle

Kąt rozwarcia stożka strugi paliwa w silniku Fiat MultiJet

Streszczenie

W artykule przedstawiono wzory empiryczne umożliwiające wyznaczenie kata rozwarcia stożka strugi wtryskiwanego paliwa. Badania przeprowadzono na stanowisku dynamometrycznym wyposażony w silnik FIAT MultiJet 1.3 SDE 90 KM pracujący według charakterystyk obciążeniowych przy prędkościach obrotowych wału korbowego 1750 obr/min i 4000 obr/min. Podczas badań silnik zasilany był handlowym olejem napędowym. Ponadto stanowisko dynamometryczne wyposażone było w system do pomiaru wielkości szybkozmiennych, tj. ciśnienia w cylindrze, ciśnienia w przewodzie wtryskowym oraz przebiegu prądu sterującego pracą wtryskiwacza. Ponadto mierzono moment obrotowy. Na podstawie przeprowadzonych badań na stanowisku dynamometrycznym i w oparciu o wzory empiryczne opracowane przez Kuleshov i Mahkamov, Sitkei, Reitz i Bracco oraz Hiroyasu i Arai wyznaczono kąt rozwarcia stożka strugi.

Słowa kluczowe: silnik spalinowy, parametry strugi paliwa, kąt rozwarcia stożka strugi

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