Article citation info:
SOCHACZEWSKI, R., CZYŻ, Z., SIADKOWSKA, K. Modeling fuel injector two-stroke diesel engine. *Combustion Engines*. 2017, **170**(3), 147-153. DOI: 10.19206/CE-2017-325

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CE-2017-325

Modeling a fuel injector for a two-stroke diesel engine

This paper discusses the modeling of a fuel injector to be applied in a two-stroke diesel engine. A one-dimensional model of a diesel injector was modeled in the AVL Hydsim. The research assumption is that the combustion chamber will be supplied with one or two spray injectors with a defined number of nozzle holes. The diameter of the nozzle holes was calculated for the defined options to provide a correct fuel amount for idling and the maximum load. There was examined the fuel mass per injection and efficient flow area. The studies enabled us to optimize the injector nozzle, given the option of fuel injection into the combustion chamber to be followed.

Key words: *diesel engine, two-stroke, fuel injector, modeling*

1. Introduction

The targeted measures to decrease fuel efficiency, emissions and improve power-to-density ratio are important not only in internal combustion engines in automotive applications but also engines in aviation applications. So, research is continued to introduce innovative technologies or upgrade the so far known ones that due to their materials or unconventional solutions could not be applied before. One of them is the opposed-piston two-stroke diesel engine [10, 13, 18]. When compared with standard engines, it shows many advantages, including:

– its combustion chamber is the space limited by two pistons reciprocating in a single cylinder line, which means no need to use heads and reduces heat loss,
– no valve mechanism and no loss due to its driving,
– reciprocating cylinders favor engine balance.

Its disadvantages are:

– a gearbox connecting two crankshafts or a complex crank system with a single shaft,
– a fuel injector inside a liner is perpendicular to the axis of the cylinder – a nozzle is selected for a given combustion chamber.

A special combustion chamber requires a new design of a fuel nozzle. Defining an injector nozzle is expensive and long-term. To speed up optimization and reduce the number of experiments, a technique of numerical modeling is applied. The literature describes many models of operation of injectors in a commona rail system: identifying capabilities of multiple injection to reduce the emissions of particulates and nitrogen oxides [1], macro- and microscopic behavior of the dynamics of multiple injection [5, 7], modeling a control valve to describe the impact of cavitation on losses in flow [2, 9, 17]. There are also strength tests of injector's elements to specify stresses and deformations in the injector due to injection-generated external loads [11], [15]. Both individual elements [1, 5, 7, 9] and the entire fuel injection systems [12, 17, 20, 21] are modeled.

When a fuel injector for a given combustion chamber is designed, previously specified nozzle parameters should be optimized by simulation. For given operating conditions (fuel pressure, amount of fuel injected, injection time, etc.), the number and diameter of nozzle holes should be determined first. These parametrs can be determined mathematically from the correlation of mass flow rate. Another method is the simulation to specify more parameters that have an impact on injector mass flow rate. The so obtained research results, e.g. mass flow rate of fuel injected can be used as an input for the next stage of combustion research.

One of the tools to model injection systems is AVL software of BOOST-HYDSIM. This is a program dedicated to the dynamic analysis of hydraulic and hydro-mechanical and control systems [3, 4, 6, 19]. It is based on the theory of fluid dynamics and vibration of multi-body systems. The main application area of BOOST Hydsim is the simulation of fuel injection.

This research combines a mathematical analysis and modeling to correctly select an injector nozzle for an opposed-piston two-stroke diesel engine. The research enables us to specify a diameter and number of nozzle holes to inject enough fuel at idling and the maximum load.

2. Principles of the model

The minimum and maximum amounts of fuel were determined from the AVL Boost calculations for an engine cooperating with a given propeller (third-degree curve) that can load of 100 kW at 4000 rpm. As a result, there was created fuel vs. power characteristics (Fig. 1) and the characteristics of compression pressure, maximum pressure and mean cylinder pressure (Fig. 2) vs. crankshaft speed. The research results are given in Table 1.

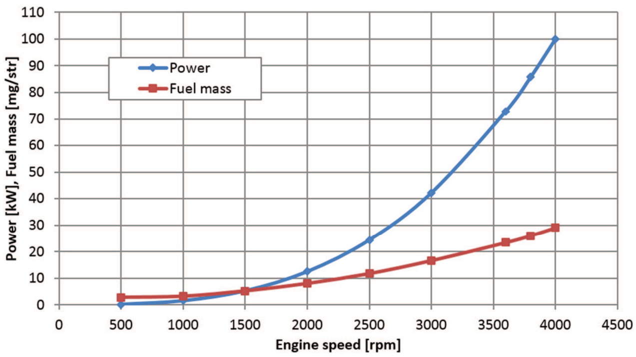

Fig. 1. Fuel amount and engine power vs. crankshaft speed

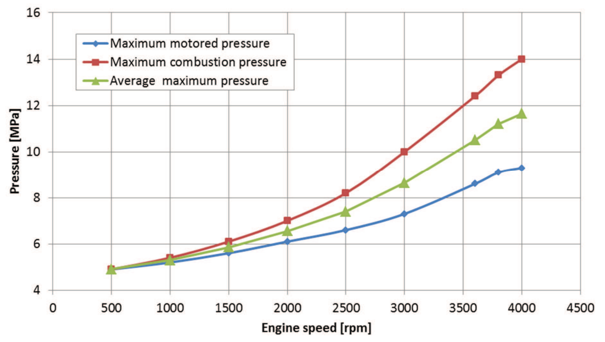

Fig. 2. Maximum motored pressure, maximum combustion pressure and average maximum pressure vs. crankshaft speed

Table 1. Research results of the propeller-loaded engine

Rotational speed	Power	Fuel mass per cylinder	Max. motored pressure	Max. combustion pressure	Average max. pressure
[rpm]	[kW]	[mg]	[MPa]	[MPa]	[MPa]
500	0.2	2.8	4.9	4.9	4.90
1000	**1.6**	**3.2**	**5.2**	**5.4**	**5.30**
1500	5.3	5.2	5.6	6.1	5.85
2000	12.5	8.0	6.1	7.0	6.55
2500	24.4	11.7	6.6	8.2	7.40
3000	42.2	16.6	7.3	10.0	8.65
3600	72.9	23.4	8.6	12.4	10.50
3800	85.7	26.0	9.1	13.3	11.20
4000	**100.0**	**29.0**	**9.3**	**14.0**	**11.65**

The results enable us to specify the boundary amounts of fuel to be injected: at idling at a crankshaft speed of 1000 rpm and for a maximum power at a crankshaft speed of 4000 rpm. Also, the boundary conditions for a cylinder, i.e. air pressure in the cylinder, into which fuel is injected were specified as mean compression pressure and the maximum pressure. The research data are given in Table 2.

Table 2. Simulation parameters

Type of operation	Rotational speed	Power	Fuel mass	Mean cylinder pressure
	[rpm]	[kW]	[mg/cylinder]	[MPa]
idle	1000	1.6	3.2	5.30
max. load	4000	100	29	11.65

To achieve a favorable air-fuel mixture, i.e. the largest possible contact surface of fuel injected with air, the fuel is assumed to be injected with one or two injectors of the number of nozzle holes as in Table 3.

Table 3. Options of the number of nozzle holes

Number of injectors per combustion chamber	Number of nozzle holes			
	2	3	4	6
1			•	•
2	•	•	•	

3. Model of an injector

Our research uses a Common Rail system injector design controlled with a solenoid valve because of the overall dimensions of the injector that define its weight and the ease of installation and arrangement of injectors on the engine. Fig. 3 depicts a model of the injector created in the Boost Hidsim.

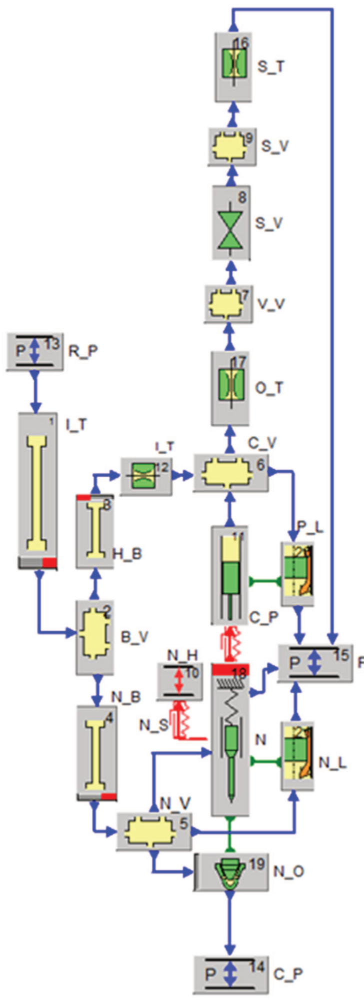

Fig. 3. Model of the injector in the Boost Hidsim

We modeled a valve closes orifice nozzle of a real geometry in which its efficient flow field is calculated from the height of the nozzle needle. The coefficient of through-the-injector-hole-flow loss is as 0.83, given that a correlation of an edge rounding and a hole diameter as r/d = 0.2 [8]. A control valve was modelled as a throttle in which the flow field is a function of time. In cooperating elements like a needle with a nozzle body and a control piston with a cylinder, there is assumed a loss due to fuel leaks. The model of fuel leaks is based on the Hagen-Poiseuille law, given a laminar flow through Annular Gap which changes according to fuel pressure [3].

A given amount of fuel is injected by estimating the minimum flow field for assumed parameters of injection and properties of the fuel. This is possible using sophisticated hydraulic models [14]. Approximate dependence was used in the studies [13]:

$$\dot{m}_e = c_d \cdot A_n \cdot \sqrt{2 \cdot \rho_f \cdot \Delta p} \qquad (1)$$

where $\dot{m}_e$ – fuel mass flow rate [mg/cycle], c_d – outflow coefficient, A_n – minimal flow field [mm^2], ρ_f – fuel density [kg/m^3], $\Delta p = (p_2 - p_1)$ – pressure difference [MPa], p_1 – combustion chamber air pressure, p_2 – injected fuel pressure. The relationship was transformed to the following formula for the minimum injection field of a single nozzle hole:

$$A_{ni} = \frac{m \cdot 360 \cdot n}{\Delta\Theta \cdot c_d \cdot i \cdot i_1 \cdot \sqrt{2 \cdot \rho_f \cdot \Delta p}} \quad (2)$$

where m – fuel mass [mg/cylinder], n – rotational speed [r/s], A_{ni} – minimum flow field of a single nozzle hole [mm^2]; $A_n = A_{ni} \cdot i \cdot i_i$; i – number of injectors per cylinder, i_i – number of nozzle holes, ΔΘ – injection time [°CA].

The diameters were determined, given that the flow through each of the injection nozzles is quasi static, incompressible and one-dimensional. The reduced diameter range was used to perform Boost Hydsim calculations. So, these were the conditions (Table 4) to investigate the injector's mass flow rate. It was assumed that there are two doses of fuel (t_1 – pilot and t_2 – main) to be injected at idling and injection pressure to be as 30 MPa. If the maximum load, there is one dose of the fuel injected at a pressure range of 100–180 MPa.

Table 4. Injection times and pressures

Number of nozzle holes	Nozzle hole diameter [mm]	Injection time [ms]	Injection pressure [MPa]
One injector			
4	$d_4 = \begin{cases} 0.14 \\ 0.16 \end{cases}$	b.j $\begin{cases} t_1 = 0.30 - 0.40 \\ t_2 = 0.40 - 0.70 \end{cases}$ max. load t_2 = 1.00	30 – idle; 100 – 180 – max. load
6	$d_6 = \begin{cases} 0.12 \\ 0.14 \end{cases}$		
Two injectors			
2	like for d_4	b.j $\begin{cases} t_1 = 0.30 - 0.40 \\ t_2 = 0.40 - 0.70 \end{cases}$ max. load t_2 = 1.00	30 – idle; 100 – 180 – max. load
3	like for d_6		
4	d_{42} = 0.10		

4. Research results

4.1. Idle

One injector

Given the values of the parameters and the calculated hole diameters, the minimal injection time when the injector completely opens was calculated. An outflow is limited by a field of injector hole but not the gap between the needle and the seat in the nozzle. The injector will not operate within a range of ballistic amounts of fuel. There are the research results of the injector operating in idling conditions. The maximum efficient flow field was compared (Fig. 5 and Fig. 7) to the flow field due to the injector hole diameter and the fuel mass per injection (Fig. 4 and Fig. 6). Table 5 and 6-hole nozzles.

4 holes

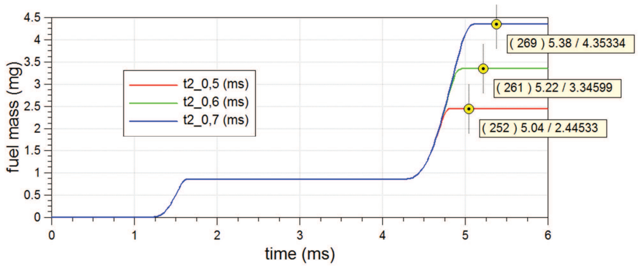

Fig. 4. Fuel mass (4-hole nozzle, t_1 = 0.4 ms; d_4 = 0.14 mm) at injection times of a main fuel dose t_2 = 0.5; 0.6; 0.7 ms

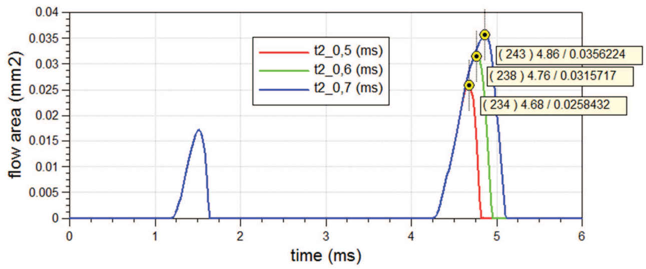

Fig. 5. Flow area (4-hole nozzle, t_1 = 0.4 ms; d_4 = 0.14 mm) at injection times of a main fuel dose t_2 = 0.5; 0.6; 0.7 ms

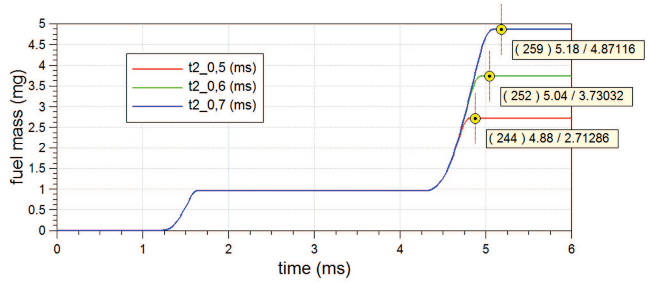

Fig. 6. Fuel mass (4-hole nozzle, t_1 = 0.4 ms; d_4 = 0.16 mm) at injection times of a main fuel dose t_2 = 0.5; 0.6; 0.7 ms

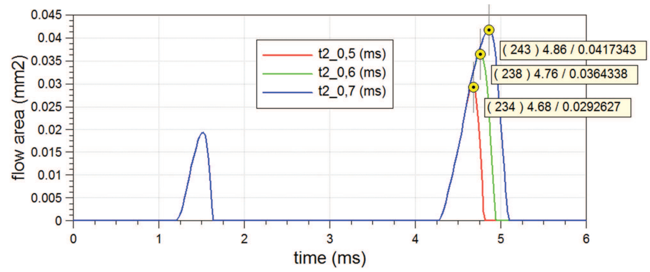

Fig. 7. Flow area (4-hole nozzle, t_1 = 0.4 ms; d_4 = 0.16 mm) at injection times of a main fuel dose t_2 = 0.5; 0.6; 0.7 ms

Table 5. Simulation for a 4-hole nozzle

Hole diameter d_4	Injection times of main fuel dose t_2	Minimum flow area	Calculated flow area	Required fuel mass	Calculated fuel mass
[mm]	[ms]	[mm^2]	[mm^2]	[mg]	[mg]
0.14	0.50	0. 01485	0.02584	3.20	2.44
	0.60		0.03157		3.35
	0.70		0.03562		4.35
0.16	0.50	0. 02186	0.02926	3.20	2.71
	0.60		0.03643		3.73
	0.70		0.04173		4.87

Given the diameters as d_4 = 0.14 and 0.16 mm and injection times of main fuel doses as t_2, the flow field is minimal in the assumed range. This means that the main doses are injected within a non-ballistic range. At the same time, if injecting the pilot dose t_1 = 0.40 ms and the main dose $t_2 \approx$ 0.60 ms, the required dose at idle is achieved.

6 holes

Given the diameters d_6 = 0.12 and 0.14 mm and injecting the main fuel doses of t_2, the flow field is minimal in the assumed range. This means that the main doses are injected within a non-ballistic range. At the same time, if injecting the pilot dose t_1 = 0.40 ms and the main dose $t_2 \approx$ 0.5–0.60 ms, the required dose at idle is achieved.

Table 6. Simulation for a 6-hole nozzle

Hole diameter d_6	Injection times of main fuel dose t_2	Minimum flow area	Calculated flow area	Required fuel mass	Calculated fuel mass
[mm]	[ms]	[mm^2]	[mm^2]	[mg]	[mg]
0.12	0.50	0.01221	0.03152	3.20	3.00
	0.60		0.03815		4.11
	0.70		0.04258		5.36
0.14	0.40	0.01457	0.02358	3.20	2.29
	0.50		0.03647		3.36
	0.60		0.04533		4.65

Then, the injection of a dose at the maximum load for the given variations should be investigated.

a) Two injectors

2 and 3 holes

Given the number of nozzle holes as 2, 3 and 4, the nozzle hole diameter to inject a fuel dose at idle as 1,6 mg/injector was calculated. By changing the correlation between the number of injectors and the number of nozzle holes, identical nozzle hole diameters were achieved. This fact refers to a 2- and 3-hole nozzle. The difference may be due to the fact that for a less number of nozzle holes, the minimum flow field can be achieved at a less elevated nozzle needle so shorter injection times. Accordingly, there was verification calculation for the given hole diameter of 2- and 3-hole nozzles, injection times, idling pressure and maximum load. The research results are given in Table 7 and Table 8.

Table 7. Simulation for a 2-hole nozzle

Hole diameter	Injection times of main fuel dose t_2	Minimum flow area	Calculated flow area	Required fuel mass	Calculated fuel mass
[mm]	[ms]	[mm^2]	[mm^2]	[mg]	[mg]
0.14	0.50	0. 01485	0.01382	1.60	1.35
	0.55		0.01533		1.57
	0.60		0.01647		1.82
0.16	0.50	0.02186	0.01585	1.60	1.51
	0.55		0.01775		1.77
	0.60		0.01930		2.05

The minimum flow field is achieved for both hole diameters when injecting the main dose $t_2 > 0.55$ ms, whereas an idling dose is achieved by injecting the pilot dose $t_1 = 0.40$ ms and the main dose $t_2 \approx 0.55–0.6$ ms.

The calculations for a 6-hole nozzle show that it is possible to inject an idling dose if nozzle diameters are $d_6 = 0.12$ and 0.14 mm. However, for a dose at the maximum load for the diameter of $d_6 = 0.14$ mm, injection pressure and injection time of the main dose t_2 should be significantly increased (Fig. 13, Table 11). Accordingly, one type of a hole diameter, i.e. $d_3 = 0.12$ mm only was assumed for a 3-hole nozzle. The injection time of the main dose was also reduced. The research results are given in Table 8.

Table 8. Simulation for a 3-hole nozzle

Hole diameter	Injection times of main fuel dose t_2	Minimum flow area	Calculated flow area	Required fuel mass	Calculated fuel mass
[mm]	[ms]	[mm^2]	[mm^2]	[mg]	[mg]
0.12	0.40	0. 01138	0.01203	1.60	1.17
	0.45		0.01480		1.42
	0.50		0.01702		1.69

Given the diameter $d_3 = 0.12$ mm and injecting the main fuel doses $t_2 > 0.40$ ms, the flow field is minimal. At the same time, if injecting the pilot dose of $t_1 = 0.40$ ms and the main dose of $t_2 \approx 0.5$ ms, the required dose at idle is achieved.

4 holes

Analogue calculations as for a 1-nozzle injector were performed for a 4-hole injector. A hole diameter for a 4-hole nozzle was calculated as $d_4 = 0.10$ mm and calculations for idling were performed. The main dose injection times were as $t_2 = 0.40$; 0.45; 0.50 ms. The research results are depicted Fig. 8, Fig. 9 and Table 9.

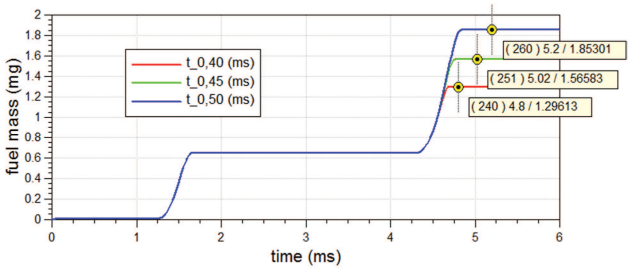

Fig. 8. Fuel mass (4-hole nozzle, $t_1 = 0.4$ ms; $d_4 = 0.10$ mm) at injection times of a main fuel dose $t_2 = 0.40$; 0.45; 0.50 ms

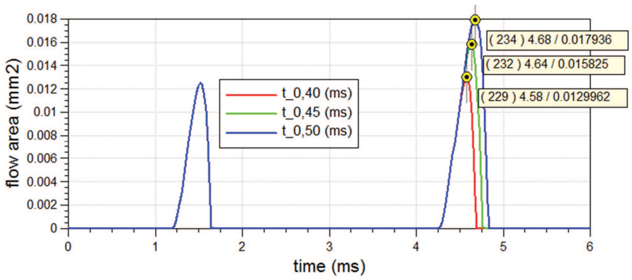

Fig. 9. Flow area (4-hole nozzle, $t_1 = 0.4$ ms; $d_4 = 0.10$ mm) at injection times of a main fuel dose $t_2 = 0.40$; 0.45; 0.50 ms

Table 9. Simulation for a 4-hole nozzle

Hole diameter	Injection times of main fuel dose t_2	Minimum flow area	Calculated flow area	Required fuel mass	Calculated fuel mass
[mm]	[ms]	[mm^2]	[mm^2]	[mg]	[mg]
0.10	0.40	0.00796	0.01300	1.60	1.27
	0.45		0.01583		1.57
	0.50		0.01794		1.85

Given the diameter $d_4 = 0.10$ mm and injecting the pilot dose at $t_1 = 0.40$ ms and the main dose at $t_2 > 0.40$ ms, the minimal flow field and the required dose at idle are achieved.

4.2. Maximum load

a) One injector

4 holes

Given the nozzle hole diameters calculated at idling, the mass flow rate of an injector at the maximum load was calculated. The amount of fuel under such conditions is about 29 mg/cylinder injected as a single dose. The calculation principles are as follows: fuel injection is as injecting the main dose, main dose injection time is $t_2 = 1.0$ ms, fuel injection pressure is p = 120–180 MPa.

The simulation results are given in Fig. 10, Fig. 11 and Table 10.

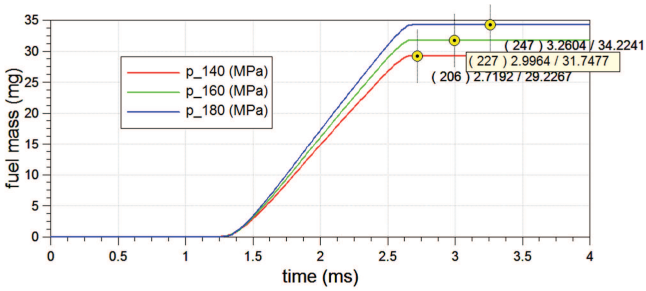

Fig. 10. Fuel mass (4-hole nozzle, t_2 = 1.0 ms; d_4 = 0.14 mm) at injection pressures as p = 140, 160, 180 MPa

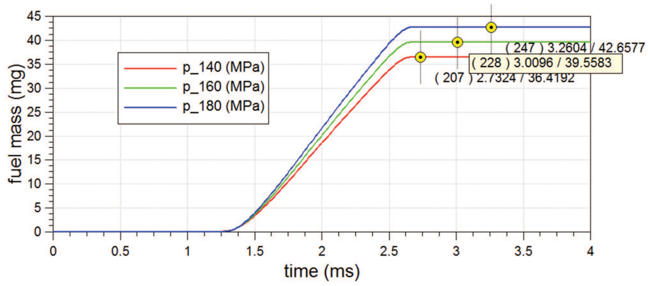

Fig. 11. Fuel mass (4-hole nozzle, t_2 = 1.0 ms; d_4 = 0.16 mm) at injection pressures as p = 140, 160, 180 MPa

Table 10. Simulation for a 4-hole nozzle

Hole diameter	Fuel pressure	Required fuel mass	Calculated fuel mass
[mm]	[MPa]	[mg]	[mg]
0.14	140	29.00	29.23
	160		31.75
	180		34.22
0.16	140		36.42
	160		39.56
	180		42.66

For the maximum load, it is better to use the hole diameter in a 4-hole nozzle as d_4 = 0.14 mm. Due to the large mass flow rate for a diameter nozzle as d_4 = 0.16 mm, fuel injection pressure or main dose injection time should be reduced.

6 holes

The hole diameters in a 6-hole injector are d_6 = 0.12 and 0.14 mm. The mass flow rates for this type of injector at the maximum load were calculated at injection pressures of 120 to 180 MPa according to the nozzle hole diameters. Fig. 12 and Fig. 13 show the mass of injected fuel for the different injection pressures. The research results are given in Table 11.

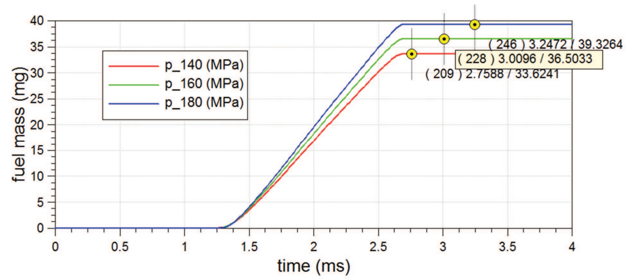

Fig. 12. Fuel mass (6-hole nozzle, t_2 = 1.0 ms; d_6 = 0.12 mm) at injection pressures as p = 140, 160, 180 MPa

Due to the large mass flow rates (d_6 = 0.12 mm) for the diameter nozzle d_6 = 0.14 mm, injection pressure was reduced to 120–140 MPa.

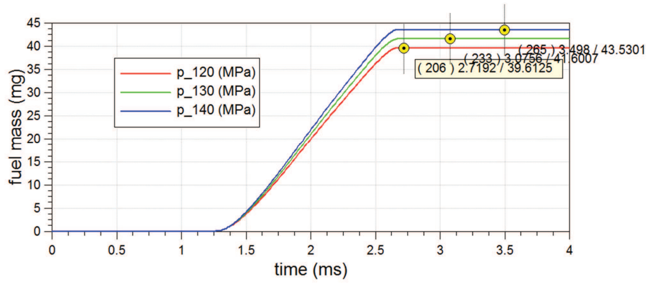

Fig. 13. Fuel mass (6-hole nozzle, t_2 = 1.0 ms; d_6 = 0.14 mm) at injection pressures as p = 140, 160, 180 MPa

Table 11. Simulation for a 6-hole nozzle

Hole diameter	Fuel pressure	Required fuel mass	Calculated fuel mass
[mm]	[MPa]	[mg]	[mg]
0.12	140	29.00	33.62
	160		36.50
	180		39.33
0.14	120		39.61
	130		41.60
	140		43.53

For the maximum load, it is better to use a nozzle hole diameter in a 6-hole nozzle as d_6 = 0.12 mm. For a diameter nozzle as d_4 = 0.16 mm, fuel injection pressure or main dose injection time should be reduced.

b) Two injectors

2 and 3 holes

Given nozzle hole diameters in a 2-hole injector calculated for idling as d_4 = 0.14 and 0.,16 mm, mass flow rates at the maximum load were calculated. The amount of fuel per injector injected under these conditions is about 14.5 mg as a single dose. The principles behind the calculations are identical as in those for a single injector.

Fig. 14 and Fig. 15 show the fuel mass for the hole diameters d_4 varied due to injection pressure. The research results are given in Table 12.

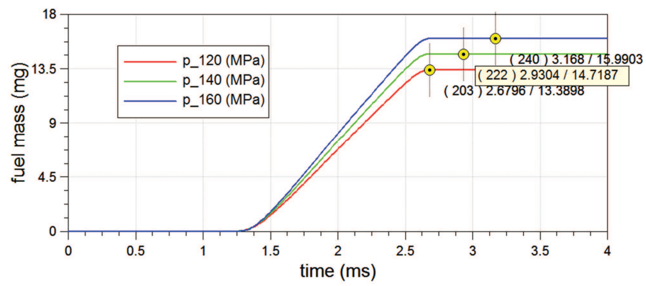

Fig. 14. Fuel mass (2-hole nozzle, t_2 = 1.0 ms; d_2 = 0.14 mm) at injection pressures as p = 120, 140, 160 MPa

A nozzle with the hole diameter of 0.16 mm, despite its low injection pressure as 100 MPa, shows a larger than required mass flow rate. Accordingly, the hole diameter of d_4 = 0.14 mm should be used in the two types of injectors with a 2-hole nozzle.

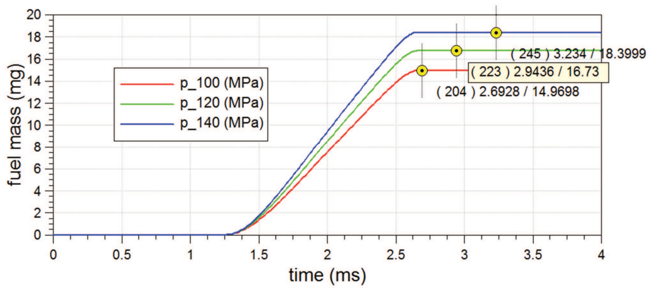

Fig. 15. Fuel mass (2-hole nozzle, t_2 = 1.0 ms; d_4 = 0.16 mm) at injection pressures as p = 120, 140, 160 MPa

Table 12. Simulation for a 2-hole nozzle

Hole diameter	Fuel pressure	Required fuel mass	Calculated fuel mass
[mm]	[MPa]	[mg]	[mg]
0.14	120	14.50	13.39
	140		14.72
	160		15.99
0.16	100		14.97
	120		16.73
	140		18.40

A mass of injected fuel for the 3-hole nozzle of a hole diameter of d_3 = 0.12 mm and injection pressures as p = 120, 140, 160 MPa (Fig. 16) was calculated At the maximum load, the required dose is achieved at the injection pressure of 120 MPa. For higher pressures, main dose injection time should be reduced (Table 13).

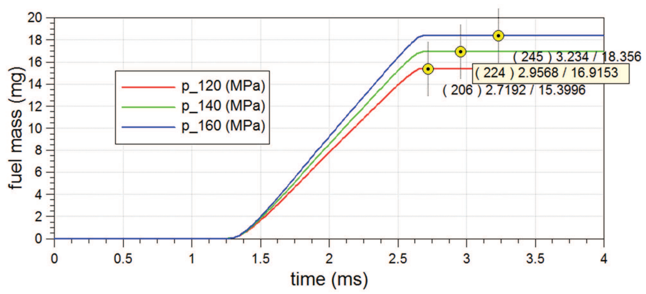

Fig. 16. Fuel mass (3-hole nozzle, t_2 = 1.0 ms; d_3= 0.12 mm) at injection pressures as p = 120, 140, 160 MPa

Table 13. Simulation for a 3-hole nozzle

Hole diameter	Fuel pressure	Required fuel mass	Calculated fuel mass
[mm]	[MPa]	[mg]	[mg]
0.12	120	14.50	15.40
	140		16.92
	160		18.36

4 holes

It was calculated a mass of injected fuel for the 4-hole nozzle of the hole diameter of d_{42} = 0.10 mm and injection pressures as p = 120, 140, 160 MPa (Fig. 16). At the maximum load, the required dose is achieved at the injection pressure of 120 MPa. For higher pressures, main dose injection time should be reduced (Table 13).

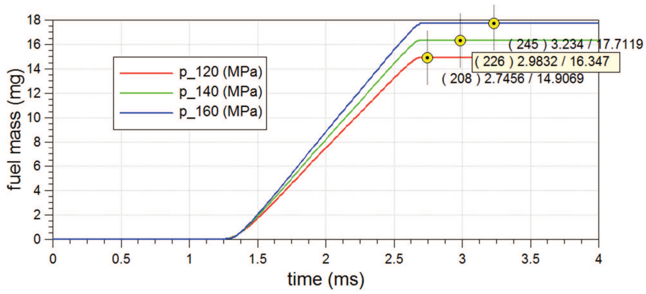

Fig. 17. Fuel mass (4-hole nozzle, t_2 = 1.0 ms; d_{42} = 0.10 mm) at injection pressures as p = 120, 140, 160 MPa

Table 14. Simulation for a 4-hole nozzle

Hole diameter	Fuel pressure	Required fuel mass	Calculated fuel mass
[mm]	[MPa]	[mg]	[mg]
0.10	120	14.50	14.91
	140		16.35
	160		17.71

Summary

Two options of injection were investigated while modeling an injector. For an input parameter, i.e. the fuel mass required at idling and the maximum load, the assumption is that the fuel is injected into the cylinder with one or two injectors. Depending on the option, the number of nozzle holes was assumed to be from 2 to 6 so the number and diameter of hole nozzles for the options were determined as follows:

a) one injector

– a 4-hole injector of a hole diameter as d_4 = 0.14 mm or optionally d_4 = 0.16 mm at reduced injection pressure or time,
– a 6-hole injector of a hole diameter as d_6 = 0.12 mm

b) two injectors

– 2-hole injectors of a hole diameter as d_2 = 0.14 mm,
– 3-hole injectors of a hole diameter as d_3 = 0.12 mm,
– 4-hole injectors of a hole diameter as d_4 = 0.10 mm.

The research results will be used to create the geometry to develop nozzles for a given fuel injector to perform bench tests. Such research will enable us to determine the mass flow rate and characteristics of the injectors. The mass flow rated calculated will be entered into the AVL Fire to optimize the combustion process.

Acknowledgement

This work has been realized in the cooperation with The Construction Office of WSK "PZL-KALISZ" S.A." and is part of Grant Agreement No. POIR.01.02.00-00-0002/15 financed by the Polish Nation-al Centre for Research and Development.

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