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# The influence of in-nozzle cavitation on flow characteristics and spray break-up

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#### ABSTRACT

In the presented paper, a combined experimental and numerical study was carried out in order to study the influence of in-nozzle flow, cavitation and tested fuel properties on the spray development and primary break up process. The internal flow of neat diesel and neat rapeseed oil biodiesel fuel in single-hole diesel injectors was studied numerically using the AVL FIRE computational program. The spray development and break-up were monitored in a pressure chamber at high pressure using a high-speed camera. An innovative method for obtaining spray length and cone angle was developed using LabVIEW software. The developed method allows us to study the influence of in-nozzle cavitation inception on the symmetry of injected fuel spray. The obtained numerical results show that the geometry of the test injector influences internal flow and cavitation inception highly. Experimental results indicate that tested fuel properties' influence spray length and cone angle at high atmospheric pressure is rather small. The cavitation inside the injector nozzle influences the primary spray break-up process further and causes part of the spray, where more cavitation is present in the nozzle hole and its exit, to disintegrate. This confirms that cavitation inside the fuel injector can have a positive effect on the spray break-up and spray disintegration process.

#### 1. Introduction

Global demand for energy is growing. Oil is currently the most consuming energy source, especially in the transport sector, where it represents 95% of all of the energy required [1]. Fossil fuels are also the main energy source in the electricity generation process [2]. The usage of fossil fuels has been proved as one of the biggest sources of produced greenhouse gas emissions [3]. The transport sector contributes around 24% of total produced greenhouse gas emissions. Biofuels, specially second generation biofuels, are considered as medium to long-term alternatives to fossil fuel, which can contribute to a reduction of harmful emission formation [4]. It is believed that they will have the most promising impact on emission formation reduction in future [1]. Currently, first generation biodiesel fuels represent 95% of world biodiesel production and are, considering this, the main source for achieving European demand for their usage and emission reduction [5]. The production of biofuels can also help to reduce region dependence on imported energy sources and their market price variation [6].

Fuel properties have great impact on the emission formation process, which is also influenced by conditions in combustion chamber and fuel injection system properties. They influence fuel flow conditions in the injection nozzle hole and spray formation process, which influences fuel evaporation rate, flame structure, etc. further [7]. Sufficient atomization (dispersion) of fuel droplets can only be achieved by combining high injection pressures with usage of injection nozzles with several small diameter injection holes. This combination promotes cavitation inception and the possibility for cavitation erosion within the nozzle holes. The cavitation phenomena in a fuel injection system can also contribute to a better atomization process of fuel spray [8]. The occurrence of cavitation in an injection nozzle hole is influenced by an engine and its injection system operating conditions [8] and by injection system geometry [9]. Engine operating conditions influence fuel injection pressure which, further, influences cavitation layer evolution speed and intensity [8,9]. Higher injection pressure influences the formation of larger cavitation areas. He et al. in [10] study how different length-diameter ratios of injection nozzle holes influence fuel flow condition in the nozzle hole, cavitating flow pattern and spray characteristics. Spray characteristics can also be manipulated by special fluid control method or special nozzle design, which is capable of manipulating the droplet size by controlling the secondary flow rate in the nozzle hole [11]. Most of the work in this research field combines numerical and experimental studies.

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Experimental studies of fuel flow in nozzle holes are performed using various real size and scaled-up optically transparent nozzles or their models. In real size models, the cavitation appears in the form of cavitation pockets (clouds) [12], while the cavitation in scaled-up models appears in the form of string cavitation [10]. Experimental observation of spray development dynamics can be performed by usage of various techniques. In most of the studies, high-speed cameras are used for monitoring of spray development in specially designed transparent pressure chambers. Conditions inside the fuel injection nozzle can also be observed using the Laser Doppler velocimetry or Particle Image Velocimetry methods [13,14].

In recent decades, numerical models have undergone great development, which has increased their accuracy. Using modern, numerical programs, experimental testing can be replaced with numerical experiments in several research and engineering fields [15,16]. Numerical simulations using Computational Fluid Dynamic (CFD) programs allow us to determine flow conditions like velocity, cavitation inception, etc. without affecting flow. The fuel flow conditions in the nozzle hole and spray development process can be analyzed numerically using RANS or LES approaches [17].

Agarwal et al. [18], tested how usage of Karanja and Jatropha biodiesel fuel in a min-sac nozzle hole with six symmetrical cylinder holes influenced flow conditions, cavitation inception and spray formation. They concluded that the physical properties of fuel have profound influence on nozzle flow condition, cavitation inception, spray atomization and evaporation characteristics. Critical parameters which influence the spray development process are fuel turbulence, velocity and cavitation at the nozzle hole exit. The spreading of a cavitation cloud in an injection nozzle hole is influenced by fuel viscosity. Fuels with higher viscosity inhibit cavitation spread [18]. Xue et al. [19], investigated numerically how an asymmetrical design of injection nozzle influences flow conditions and cavitation inception in each nozzle hole. They concluded that a higher nozzle holes' angle, defined as angle between the injection needle and injection holes' axes, contribute to a higher degree of cavitation formation and developments in the sac nozzle.

Agarwal et al. [18,20], reported in their study, that higher ambient pressure in the combustion chamber influences the spray development process when using diesel and biodiesel fuels. Higher ambient pressure influences decrease of spray length and increases the spray cone angle. Spray development parameters are also influenced by ambient temperature. Wang et al. in [21] demonstrated that lower ambient temperature has influence on poorer spray dispersion, which leads to formation of larger fuel ligaments. They also concluded that the spray development process is influenced by fuel conditions at the nozzle hole exit, which depends on the fuel flow condition inside the hole.

The increase of fuel mass flow rate (injection rate) results in an increase of fuel velocity from zero to higher values as the mass flow increases. The ambient gas in a combustion chamber is quiescent in the early stage of the injection process. This decelerates fuel droplets and influences the wider spray cone angle at the start of the injection process. With an increase in the fuel injection rate, the ambient gas in the injection (combustion) chamber starts to move. This decreases the drag force acting on the fuel jet and increases fuel spray injection velocity, which reaches its maximal value shortly after the start of injection. After reaching maximal value, the spray injection velocity starts to decrease and reduces the gradient of spray length development [22,23].

In the presented paper, fuel flow conditions of mineral diesel fuel and rapeseed oil biodiesel fuel, as one of the most used biodiesel fuel in the EU, where tested numerically using the AVL FIRE program. The study was performed using the geometry of a single injection hole fuel injector designed for engines with an M-injection system. The main difference between our injector and the injectors used in the presented studies is in the single hole design and its diameter of 0.68 mm. This diameter is 3–4 times greater than in injectors with several injections holes, which influences the different characteristics of fuel flow in the nozzle sac volume and inside the nozzle hole. We expect that the majority of fuel will flow into the injector hole from the bottom and sides of the nozzle sac volume, which will cause the cavitation inception region to be at the bottom side of the nozzle hole. This is different compared to fuel flow in nozzles with several holes, where the majority of the fuel for each hole flows from the upper area between the nozzle needle and injector body. In the second part of the presented study, spray development was monitored experimentally in a transparent high pressure injection chamber. The spray development photos were used for determination of spray cone angle, length and velocity. They also allowed us to monitor the primary spray break-up process dynamic. Numerically obtained results of internal nozzle hole flow were used to study the influence of cavitation inception and nozzle hole influence on spray primary break-up.

The study of fluid flow condition and cavitation inception in a single hole fuel injector, and influence of cavitation on the spray primary break-up process was not found in previously presented studies. It presents new insight on how injector geometry influences fuel flow conditions and the influence of cavitation inception on spray disintegration. In a single nozzle hole fuel injector all fuel flows through only one nozzle hole and forms only one fuel spray. This excludes any interaction between fuel sprays and lowers the amount of fuel vapor in transparent pressure chamber.

#### 2. Tested fuels

During the presented study, neat diesel fuel D2 that contains no additives, and neat rapeseed oil biodiesel fuel B100 produced from rapeseed oil at Biogoriva Rače, Slovenia were used. The tested fuel properties are presented in Table 1 and Fig. 1.

Different test methods, which corresponded to European or other standards, were used to measure fuels' properties presented in Table 1. The fuels' densities were measured at 15 °C according to the European standard EN ISO 12185, kinematic viscosities were measured at 30 °C using a test method confirming the European standard EN ISO 3104, and the fuels' compositions were measured using the test method ASTM D 5291. Other presented fuel properties were supplied by producers of diesel and rapeseed oil biodiesel fuels and were not further tested.

Values of tested fuels' densities and sound velocities presented in Fig. 1 were calculated using equations presented in Ref. [6].

#### 3. Experimental set-up

Experimental measurements of spray development and break-up were performed on an injection system test bed equipped with a high pressure chamber, BOSCH PES 6A 95D 410 LS 2542 high pressure pump and BOSCH DLLA 5S834 injectors with one nozzle hole. The injection system test bed was equipped with a Data Accusation System (DAQ system) which allowed measurements of pressure at the sides of the high pressure tube ( $p_1$  and  $p_2$ ), needle lift, Camshaft Angle (CA) and the amount of injected fuel per cycle. All measurements were made under full load position, determined by pump rack position. This means that, under a single operating regime, the usage of different fuels can cause that fueling is slightly different. Detailed information about the fuel injection system and fuel injector are presented in Table 2.

Spray development was monitored in a high pressure transparent

Table	1				
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est	ted	fuel	s	pro	pert	ies.
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Fuel	D2	B100
Density at 15 °C (kg/m <sup>3</sup> )	838.8	884.8
Kinematic viscosity at 30 °C [mm <sup>2</sup> /s]	3.34	5.51
Lower caloric value [MJ/kg]	42.8	38.2
Cetane number	45	51



Fig. 1. Tested fuels' densities and sound velocities

Table 2Fuel injection system and injector specification.

Fuel injection pump type	Bosh PES 6A 95D 410 LS 2542
Fuel injector type	BOSCH DLLA 5S834
Pump plunger (diameter $\times$ lift)	$9.5\mathrm{mm}  imes 8\mathrm{mm}$
Fuel tube (length $\times$ diameter)	1024mm  imes 1.8mm
Injection nozzle (number × nozzle hole diameter)	$1 \times 0.68  \text{mm}$
Maximal needle lift	0.3 mm

chamber which was pressurized using nitrogen (N<sub>2</sub>) gas. The desired atmospheric pressure of 60 bar in the pressure chamber was adjusted using a pressure reduction valve. The nitrogen in the pressure chamber was replaced after each measurement in order to lower the amount of fuel vapor in the pressure chamber. Specially designed LED lights were used for illumination of spray development in the pressure chamber. Photos of spray development were taken using a digital Fastec HiSpec 4 high-speed camera at a resolution of  $128 \times 332$  pixels and frame rate 18,500 fps. The experimental set-up is presented schematically in Fig. 2.

The injection test bed DAQ system was synchronized with a highspeed camera signal which enabled us to determine at which CA angle or time of injection each photo of spray development was taken. National Instruments USB-6255 with SCXI 1520 was used for acquisition of pressure  $p_1$  and  $p_2$  signals, needle lift position (according to TDC) and camera sync out data acquisition. All signals were acquired simultaneously at 100 kHz sampling rate. The application for data acquisition was made in the LabVIEW program environment and allowed us to monitor and save all needed experimental data during measurements.

#### 3.1. Design of experiment

The experimental measurements were performed at 500 rpm, 800 rpm and 1100 rpm pump rotation speeds and 40–60 bars of atmosphere pressure in transparent injection chamber. The selected chamber pressures presents typical in-cylinder pressures during the main injection process. At each atmosphere pressure all pump rotation speeds were tested, one at the time. After each measurement the nitrogen in the pressure chamber was replaced in order to reduce amount of fuel vapor in chamber. All tests were made at full engine load, determined by pump rack position, where the maximal amount of fuel is injected at each operating regime.

Neat diesel fuel and neat rapeseed oil biodiesel fuel where used in presented study. Selected fuels present extreme values for all diesel – rapeseed oil biodiesel fuel mixtures so the results obtained in presented study can easily be applied to all fuel mixtures made from fuels tested.

In the presented study only the result at rated power conditions – 1100 rpm pump rotation speed where used. At this regime the injection time is the shortest so the fuels mass flows are the highest which presents the most rigid operating conditions at which we expect that the cavitation phenomena flow characteristics and spray break-up will be the most influential.



Fig. 2. Experimental set-up.



#### 4. Numerical model

Numerical simulations of fuel flow in the injection nozzle tip were performed using the AVL FIRE CFD program. The numerical model was made for only one half of the whole injection nozzle tip and the symmetry boundary condition was used for other part of the injection nozzle. The computational mesh of the fuel injector is presented on Fig. 3. In order to avoid the influence of the boundary settings on the hole's outlet on the calculation results, the calculated fluid domain has been expanded (a small cylinder has been added at the hole outlet). During the simulation the injector needle was fully open.

The selected mesh has 1.25 million of Hexcell elements. Along the whole body of the nozzle, small cell sizes were used in order to obtain detailed results of cavitation formation.

The dynamics of transient fuel flow were considered by changing the fuel injection rate (mass flow) at the inlet boundary condition. The fuel injection rate used at the inlet boundary condition is presented in Fig. 4. The fuel properties presented in Table 1 were implemented within the FIRE program in order to include the real properties of diesel and rapeseed oil biodiesel fuel in the numerical simulation.

#### 4.1. Mathematical models

Three different approaches are used commonly when simulating cavitation flow within nozzle holes. These approaches are using the homogeneous flow approach, volume-of-fluid approach or two-fluid approach. The two-fluid model approach calculates all conservation equations for each phase, while the other two approaches calculate the volume fraction of each phase and solve only single momentum or enthalpy equations [24]. As shown in [25], the two-fluid model approach gives a detailed description of flow with less amount of computational time needed. According to this, the two-fluid model, integrated in FIRE software, was used in the presented study. Some of the important models' equations are presented in this paper. For a detailed description of the modes please refer to [24].

The governing mass and momentum conservation equations, based on Reynolds average Navier-Stokes (RANS) equation, can be written as:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot \alpha_k \rho_k v_k = \sum_{l=1, l \neq k}^2 \Gamma_{kl}$$
(1)

$$\frac{\partial \alpha_k \rho_k \nu_k}{\partial t} + \nabla \cdot \alpha_k \rho_k \nu_k \nu_k = -\alpha_k \nabla p + \nabla \cdot \alpha_k (\tau_k + \tau_k^t) + \alpha_k \rho_k g + \nu_k \sum_{l=1, l \neq k}^2 \Gamma_{kl} + \sum_{l=1, l \neq k}^2 M_{kl}$$
(2)

where k equals 1 for the pure gas phase and 2 for the pure liquid phase only.  $v_k$  and  $\rho_k$  are the respective velocity and density at phase k.  $\Gamma_{kl}$ denotes the interfacial mass transfer between phases k and l,  $\tau_k$  represents the shear stress and  $\tau_k^t$  the Reynolds stress at phase k.  $M_{kl}$  is the interfacial momentum transfer between phases k and l.  $\alpha_k$  is the volume fraction of phase.

The sum of volume fractions is calculated using Eq. (3) as:

$$\sum_{k=1}^{2} \alpha_k = 1 \tag{3}$$

Interfacial mass exchange was calculated using linear cavitation as:

$$\Gamma_{12} = \rho_d N''' 4\pi R^2 \dot{R} = \Gamma_{21} \tag{4}$$

where  $N^{m}$  is the bubble number density, R is the mean bubble radius in the cavitation region and  $\dot{R}$  is the change rate of bubble radius. The linear cavitation model predicts that the governing force for mass exchange is the pressure difference between phases  $\Delta p$ .

$$\Delta p = p_{sat} - \left( p - \frac{2}{3} \rho_c k_c \right) \tag{5}$$

In Eq. (5)  $p_{sat}$  represents fuel saturation pressure.

The turbulence modeling in the presented work was done using a standard $k-\varepsilon$  turbulence model. Standard wall function equations were used to compute the near wall region's turbulent flow.



Fig. 4. Injection rates.



Fig. 5. Base image (a) Image of spray jet (b) Subtracted image (c).

#### 5. Spray visualization method

Spray visualization was performed in a high pressure chamber in which fuel was injected and monitored using a high-speed camera. The nature of the fuel spray's development caused it to disintegrate into small droplets which break off from the spray body and evaporate. This causes the formation of fuel fog in the injection chamber and makes it difficult to determine the exact spray length and cone angle, especially at the end of the injection process.

The images were analyzed separately one at the time. Generally, only the images from the first few injections were suitable. The quality of the rest was obscured by fuel fog. Image analysis was adjusted to reduce the influence of the fog. An assumption was made that the surrounding fuel fog moves much slower than the fuel spray jet. An image just before the injection was used as the basis for further analysis. Index of the image closest to the desired needle lift or desired position before TDC was selected from the data acquired by the data acquisition system for several cycles. Images were converted into two-dimensional arrays of values up to 255 (8 bit) for further analyses. Each array presents the image under analysis subtracted from the base image. This procedure proved to be beneficial to handling of other image shortcomings like inconstant illumination and sporadic spots on the windows. A histogram analysis of all values was performed to define the background. It was possible to adjust the percentage of values considered as background.

Detailed analysis was performed on a line-to-line basis. Each n-th line was extracted and the maximum value selected. Threshold value (as a percentage of maximum value) was selected, and the starting and ending indexes represented the spray borders. The line where no or negligible numbers of values exceeding the background value could be found presented maximum spray length.

#### 6. Results

The influence of the physical-chemical properties of tested fuels on in-nozzle flow, cavitation inception, spray jet development and primary break up process were tested in the presented paper. The test was made using pure mineral diesel and rapeseed oil biodiesel fuels in a mechanical controlled injection system which has injectors with only one injection hole. In the following chapter, only the most relevant results are presented at different times of the injection process ( $T_{S1} = 0.6 \text{ ms}$ ,  $T_{S2} = 0.9 \text{ ms}$ ,  $T_{S3} = 1.2 \text{ ms}$ ,  $T_{S4} = 1.35 \text{ ms}$  and  $T_{S5} = 1.65 \text{ ms}$ ). The selected times coincide with the moments at which the most phenomena (phenomena transition) or changes occur in the injection nozzle hole. The atmospheric pressure in the high pressure injection chamber was set at 60 bars. The same pressure was also used as the boundary condition in numerical simulations.

#### 6.1. In-nozzle flow

The influence of tested fuel properties on in-nozzle flow and cavitation formation was tested numerically. Simulations were made using the AVL FIRE CFD program at maximal engine power operating condition (2200 engine rpm = 1100 pump rpm). The most relevant results of in-nozzle flow are presented in Figs. 6 and 7.

From the presented results, it can be seen that the vapor fraction appears at  $T_{S1}$ , which coincides with the time 0.6 ms. The vapor – cavitation fraction first occurs at the start (inlet) of the nozzle hole. As soon as the first cavitation structures are formed, the attached cavitation cloud starts to form and spreads throughout the whole nozzle hole. From the results of in-nozzle flow on symmetry boundary condition, Fig. 6, it can be seen that significantly more cavitation phase is formed at the lower part of the nozzle hole where the most of the fuel enter the nozzle hole. In this region, the fuel which flows through the injector body and sac volume makes significant changes in the flow which influences the increase of fuel velocity and forms a region with low pressure.

No major difference can be seen between diesel and rapeseed oil biodiesel fuel influence on the amount of formatted vapor phase.

After a short period, the vapor region formed in nozzle hole reaches the hole outlet. In the presented study, this occurs between  $T_{S2}$  and  $T_{S3}$ . The results of vapor volume fraction on hole outlet are presented in Fig. 8.

The results presented in Fig. 8 indicate that the fuel properties of diesel and rapeseed oil biodiesel don't have major influence on the amount of vapor fraction at the nozzle hole outlet.



Fig. 6. In-nozzle flow on symmetry boundary condition.

The results indicate that significant more vapor is present at the lower part of the hole outlet (left side of hole outlet cuts). This coincides with the presented results in Fig. 6, where more vapor fraction is formed at the lower part of the nozzle hole. From the presented results, we assume that vapor at the lower part of hole outlet will influence the spray break up process in the area near to the hole exit where primary spray break up occurs.

Fuel mass flow also influences Average Turbulent Kinetic Energy (ATKE) at the nozzle hole exit, Fig. 9.

With an increase of the fuel injection rate, the Average Turbulent Kinetic Energy at the nozzle hole exit also increases, Fig. 9. The maximal fuel flow rate is achieved at around 2 ms of fuel injection process, while the results of ATKE show that the first peak of maximal ATKE is achieved around 1.2 ms after the start of injection. This collides with time  $T_{S3}$  where vapor fraction reaches the nozzle exit. This indicates that the magnitude of turbulent kinetic energy increases with the increase of fuel mass flow rate, but it is also influenced by the appearance of the vapor phase at the nozzle hole exit.

#### 6.2. Spray development

For the purpose of spray development, monitoring spray penetration length and cone angle were determined from the obtained experimental results using the previously presented spray visualization method made in the LabVIEW program. Spray length and cone angle were monitored only in the first 1.8 ms of spray development. After that time of



Fig. 7. In-nozzle flow - back side of injector nozzle tip.

injection, large amounts of fuel vapor and droplets are formed and present in the area surrounding the spray, which makes it hard to determine the exact spray length. Spray cone angle was determined at 1/3 of spray length for each photo. The results of spray length and cone angle are presented in Fig. 10.

The presented results of spray length indicate that spray length increases more or less linearly during the whole presented interval. A small difference between the developments of spray length can be seen on detailed inspection. In the first 0.2 ms, the gradient of spray length is smaller compared to the next interval between 0.2 and 0.45 ms. In the second interval, the gradient of spray development is greater (higher) than in the previous (0-0.2 ms) and next (0.45-1.8 ms) intervals. This coincides with the highest spray velocity presented in Fig. 11.

Spray velocity results, presented in Fig. 11, are showing that, during the first interval of the injection process, spray velocity is increasing, and reaches its maximal value around 0.45 ms of the injection process. This is connected with needle lift and fuel injection rate, which increases in the first (early) stage of injection and reaches the highest

change in gradient at around 0.45 ms, Fig. 4. Spray velocity distribution is also connected with atmospheric conditions inside the high pressure injection chamber. At the first stage of injection, the nitrogen in the injection chamber is quiescent, so the front of the spray gets decelerated by the drag. This influences the lower spray velocities in the first stage of the injection process. With the penetration of first fuel droplets in the atmosphere, the cone angle of spray, presented in Fig. 10, increases. With increase of fuel injection rate, spray velocity increases and causes an increase in spray length. After the injection of first fuel droplets in the injection chamber, the movement of  $N_2$  is established, which decreases the spray drag and, consequently, the spray cone angle. After reaching the maximum value, the spray velocity starts to decrease. This influences the smaller spray length curve gradient in the last part of the monitored injection process.

#### 6.3. Spray break-up

The spray break-up process is normally divided in two parts. The

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Fig. 9. Average Turbulent Kinetic Energy at the nozzle hole exit.

first part is primary break-up, which occurs in the area close to the nozzle exit. In this part of the break-up, a liquid stream of fuel starts to form a jet and gets converted into liquid sheets and ligaments, which disintegrate further into large droplets. In the second part of the breakup process large droplets, formed in the first part of the break-up, disintegrate into smaller droplets, which evaporate in their final stage. The spray break-up process and disintegration is governed by three main mechanisms, which are aerodynamics break-up, turbulence induced break-up and break-up caused by the collapse of the cavitation structures present in the fuel jet. In the presented paper, we predicted that collapse of the cavitation structures will have significant influence on spray break-up in the region close to nozzle exit, so only the region of primary break-up is considered in the following section, Fig. 5.

The images of spray development and break-up at selected times with marked high spray disintegration regions (dotted red lines) are presented in Fig. 12.

The comparison of spray development, when using pure diesel and pure rapeseed oil biodiesel fuel at 60 bars of atmospheric pressure in an injection chamber, is presented in Fig. 12. From the presented results it can be seen that differences in tested fuel properties cause minor differences in spray shape. During the jet development, spray forms a cone like shape. A virtual cone is added to the pictures in order to highlight



the spray cone shape and allow us better visualization of the obtained results. At  $T_{S1}$  the cone of the spray is being formed. At times  $T_{S2}$  and  $T_{S3}$  the spray has more or less cone like shape. Despite the fact that the vapor fraction reaches the nozzle exit at  $T_{S3}$ , Fig. 8, no influence of cavitation on spray break-up is evident at this time. The same is evident for time  $T_{S4}$ . But, at  $T_{S5}$ , disintegration of spray can be evident in the lower right side of the spray jet. This region of high spray disintegration coincided with the region where high values of vapor (cavitation) fraction are present. In order to support the presented influence of cavitation on spray integration, the center of the spray width was determined from pictures of spray development at selected times. The results of spray center distribution in the first 12 mm of spray are presented in Fig. 13.

As can be seen from the presented results of spray center distribution In Fig. 13, the spray center moves towards the left-hand side of the pictures presented in Fig. 12. This indicates that the collapse of cavitation structures in the right side of the fuel spray contribute to disintegration of the fuel spray jet in the region of primary break-up. Because the cavitation region inside the injector hole and at its exit is highly asymmetrical, it influences the formation of an asymmetrical spray jet in the region of cavitation structure collapse.

#### 7. Conclusions

In the presented paper, numerical simulation of in-nozzle flow and experimental measurements were performed in order to study the effect of tested fuel properties on cavitation inception, spray characteristics, development and primary break-up. Neat diesel and neat rapeseed oil biodiesel fuels where used during the study. The combination of internal nozzle hole flow numerical results and spray development pictures allow us to study the effect of cavitation inception on the primary spray break-up process and disintegration. From the analyses of presented results, the following conclusions are revealed.

- Single hole design of the injection orifice influences fuel flow in the injection nozzle tip. The majority of fuel enters the injection hole from the nozzle sac volume which causes that most of the cavitation is formatted at the lower edge (side) of the injection hole.
- There are no major differences between cavitation inceptions for diesel and for rapeseed oil biodiesel fuel. This indicates that small differences in tested fuel properties do not have significant influence on cavitation inception at full engine load when using a single hole injection nozzle. At the selected test regime, nozzle geometry has the biggest influence on cavitation inception.
- After a short time from its inception, cavitation spreads throughout the nozzle hole and reaches its exit. The occurrence of vapor (cavitation) fraction at the nozzle hole exit influences the primary break-up process. The region of spray, where more vapor fraction is present at the nozzle hole exit, disintegrates better. This causes the shape of the fuel spray's jet to be asymmetric.
- At the start of the injection process, quiescent gas conditions in the injection chamber influence slower spray development velocity and



Fig. 12. Images of spray development and break-up.



Fig. 13. Spray center distribution.

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wider spray cone angle.

 The high atmospheric pressure in the injection chamber and minor differences in tested fuel properties result in small differences between the obtained spray cone angle and length for diesel and for rapeseed oil biodiesel fuels.

The presented results indicate that neat rapeseed oil biodiesel fuel can be used in engines with mechanically controlled injection systems and single hole injectors without major modification of the engine or its injection system.

The asymmetric shape of the fuel spray jet is caused by cavitation inception in the nozzle hole and collapse of cavitation structures. Numerical models (programs) for calculation of spray development dynamics should be able to consider this influence of cavitation on the spray development geometry during the simulation.

The collapse of cavitation structures in the spray jet helps towards a better disintegration and break-up process of fuel spray jet in its primary stage. This can help to better the spray break-up process in the secondary stage, where the aerodynamic mechanism has the biggest impact.

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