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# VARIABILITY OF THE DIESEL FUEL SPRAY MICROSTRUCTURE DURING THE INJECTION INTO STAGNANT AIR BY A TYPICAL DIESEL ENGINE INJECTOR

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**Key words:** fuel atomization, spray parameters, droplet size.

**Abstract:** The article presents the results of a study on the distribution of Sauter Mean Diameter (SMD) along the axis of an atomized diesel oil spray and changes in SMD occurring during the injection in selected cross-section of the spray. A piston fuel pump was used for atomization, while atomization quality measurements were made using a Malvern Spraytec particle analyzer. The results show that adopting averaged SMD values for the whole fuel spray charge does not reflect the actual range of droplet sizes in the area of highest volume concentration of droplets in a spray, i.e. the area having the greatest impact on the evaporation and combustion of fuel. It can be useful to designers of diesel engines and simulation of processes in combustion chamber.

## Zmienność mikrostruktury strugi rozpylonego paliwa podczas wtrysku do nieruchomego powietrza przy pomocy typowego wtryskiwacza do silników z zapłonem samoczynnym

**Słowa kluczowe:** rozpylanie paliw, parametry strugi, rozmiar kropel.

**Streszczenie:** W artykule przedstawiono możliwości doboru średnic kropli rozpylonego paliwa do badań modelowych lub jako wartość wzorcową (reprezentatywną) dla strugi rozpylonego paliwa w komorze spalania silnika z zapłonem samoczynnym. Zamieszczono wyniki badań rozkładu średniej średnicy Sautera (SMD) wzdłuż osi strugi rozpylanego oleju napędowego oraz zmian SMD zachodzących w czasie wtrysku w wybranym przekroju strugi. Do rozpylania użyto tłokowej pompy paliwowej, a do pomiarów jakości rozpylania przyrządu Spraytec firmy Malvern. Przedstawione rezultaty wskazują, że przyjmowanie uśrednianych wartości SMD dla zakresu rozpylania całej dawki paliwa nie odzwierciedla rzeczywistego obrazu rozmiarów kropli w obszarze najwyższego stężenia objętościowego kropel w strudze, czyli mającego największy wpływ na proces odparowania i spalania paliwa.

## Introduction

Fuel droplet diameters are essential in modeling the processes of forming and combustion of the fuel-air mixture in the combustion chamber of diesel engines. The time of transition from the liquid to gaseous phase in which fuel is ignited and burnt depends, among other factors, on fuel droplet size. The size of droplets, their surface area and spray tip penetration depend on the breakup of fuel dose.

If the assumed diameters of atomized fuel droplets are too small or too large, the effect in operational practice will be higher fuel consumption and increased emissions of harmful exhaust gas components in the actual combustion chamber. Since atomization is a statistical process, parameters such as droplet size distribution, spray cone angle and spray tip penetration vary in each successive test, even for the same atomizer and identical boundary conditions of spray formation [1]. Hence the need to use averaged values and substitute sets of uniform diameter droplets. The average volume-area diameter is used, known as Sauter Mean Diameter, (SMD) to characterize the quality of liquid atomization.

Data on a representative droplet diameter size, necessary in analyses of processes of heating, evaporation and combustion of fuel droplets in the diesel engine combustion chamber, may come from various sources:

- literature, where authors rely on the published results of experiments involving fuel atomization and combustion of a fuel spray, such as [2];
- calculations by formulas based on the theory of similarity, semi-empirical and empirical formulas, verified in experiments by available methods of spray microstructure determination, e.g. [3–5].
- determination of mean droplet diameter values by available physical methods, based on actual analysis of microstructure of real atomized fuel, for strictly defined boundary conditions e.g. [3–5].

The main parameters of fuel atomization in diesel engines, affecting the complexity level of an experiment such as measurement of granulometric distribution of droplets flowing out of the atomizer, are caused by, inter alia: a large number of droplets in a spray, order of $10^6$; high speed of droplets, exceeding 300 m/s; wide range (inhomogeneity) of droplet size; change in droplet size along the spray axis due to secondary breakup, coalescence, evaporation [6]; non-uniform distribution of liquid spray density, longitudinally, radially and circumferentially, in a selected cross-section of the spray [1].

Despite technological progress, measurements of spray microstructure remain a complicated task. The results of granulometric distribution depend not only on physical quantities listed above, but also on experiment conditions, including: overall and temporary sampling, the sample size, saturation of a sample, evaporation and coalescence of droplets, location of sampling [5].

The dynamics and complexity of the phenomena occurring during liquid atomization cause an essential problem, related to the influence of the methodology of measuring diameters and number of droplets in a real set on experimental data. Available methods, starting with the least complex, such as frozen-drop techniques to the most technologically advanced, such as light scattering, have specific capabilities and advantages, but also limitations and disadvantages. Measurement of SMD in a periodically sprayed fuel dose may lead to divergent results, depending on the method of measurement of granulometric distribution of droplets. Even the same method used, but with other measurement parameters, will yield varying results.

The source of the adopted diameter data affects the reliability of conclusions, depending on the goal of the application, type of processes under examination and the results. Previous studies [1, 3, 5, 7] of factors affecting the atomization of fuel flowing out of the nozzle show that the determination of SMD based on calculations using the theory of similarity or semi-empirical models for a specific atomizer and atomization conditions can generate important differences in the results [8–11]. This is due to relatively narrow limits of the applicability of the formulas, resulting from boundary conditions adopted during their formation, the method used and the scope of experiment parameters verifying the formula.

Mechanisms of the liquid jet breakup behind the nozzle depend on the Reynolds number Re and Ohnesorge number Oh. Depending on the values of these numbers, we can distinguish four main areas: Rayleigh's mechanism, first wind induced area, second wind induced area and atomization proper [3, 5]. Each of the breakup mechanisms produces a characteristic structure of the spray, consisting of the liquid jet and atomized droplets. As fuel flow speed from the nozzle increases, the liquid core length may increase or decrease, depending on the atomizing mechanism [5]. In the case of atomization, increase in discharge velocity will reduce the jet breakup length. In [5] the author discusses the study on the impact of the Reynolds number, differential pressure before and after the atomizer nozzle, and the nozzle length/diameter ratio $l_0/d_0$ on the jet breakup length.

The higher the density and temperature of the gas are, the shorter the liquid core is [12, 13]. Another study indicates the influence of the temperature of fuel on the jet breakup length: the higher the temperature, the smaller the liquid core length is. At the same time it was found that the nozzle diameter matters: its increase leads to a longer liquid core [13].

The presence of liquid jet in the examined spray cross-section disturbs the determination of the mean droplet diameter. Measuring instruments based on the light diffusion principle make comparisons of the values measured to a model incorporated in the software, failing to distinguish the shape of objects in the spray, and the result is the diameter of a spherical droplet.

In the literature on the subject considered herein we can also find results where the phenomena of secondary breakup and possible coalescence and evaporation of droplets are taken into account. The value of SMD changes as the fuel spray develops. Relatively large droplets at the start of injection (SOI) after a while decrease several times to a constant value [8, 9, 11, 12, 14]. Similar changes in diameters were observed for various biofuels [15].

The authors of [9, 10] cite the results of numerical tests and an experiment testing the distribution of SMD along the spray axis for different distances from the atomizer hole. In this case the values obtained in the experiment are constant, but the measuring points are relatively far from the hole (above 20 mm). Increasing the distance from the atomizer hole results in a smaller droplet diameter [9]. A constant value of SMD along the axis was obtained by the authors of [16] for two types of flow in the nozzle: smaller for cavitation flow, larger for turbulent flow, but the measurements were made at distances longer than 60 mm from the discharge orifice.

Changes in the fuel droplet diameter along the spray axis cannot be subjected to quantitative analysis, because those experiments were made for fuels of different physical parameters and in non-identical conditions. Nevertheless, all the mentioned results share one feature: droplet diameters decrease in the transition area to a certain constant value, at a specific distance from the atomizer hole, and that distance depends on the specific experimental conditions.

For the comparison of mean droplet diameters in a spray, the adopted cross-section of sampling should be clearly located outside the secondary breakup area (in the area of constant values of diameters, but close to the transition area).

Given the phenomena of secondary breakup of droplets, the coalescence resulting from the droplets crashing at each other and evaporating, which may have a significant impact on the change in droplet diameter, the location of sampling (choice of spray cross-section along its axis) is crucial for the resulting determination of mean droplet size of a fuel spray.

With the current level of measuring technology, availability of measurement devices and the quality of software enabling high frequency of sampling and relatively simple measurement procedures and available data registration functionalities, it seems natural to use the apparatus for the determination of droplet diameters and other related parameters. The main purpose is enhanced diagnostics of diesel engine fuel atomizers.

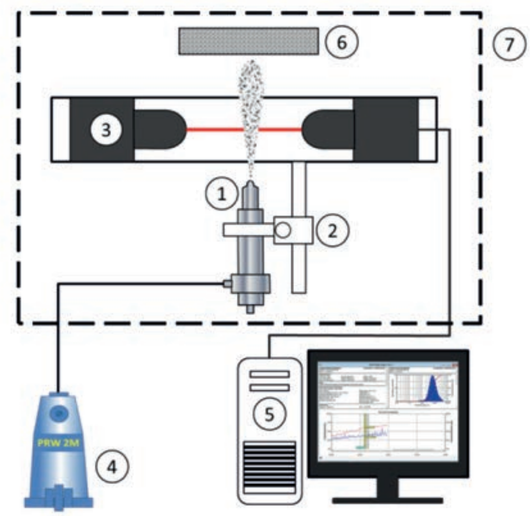


**Fig. 1. A setup for testing fuel atomization quality, 1 – fuel atomizer D1LMK 148/1, 2 – injector holder W1F-01, 3 – Spraytec, 4 – injector tester PRW 2M, 5 – a computer with monitor, 6 – fuel absorber, 7 – fume cupboard**

## 1. Materials and methods

To obtain a spectrum of atomized fuel spray the authors used a test bed built at the Marine Engineering Faculty Research Laboratory, Maritime University of Szczecin (Fig. 1).

The test set up consisted of the atomizing unit: atomizer (1), mounted on a W1F-01 injector in a holder (2), PRW 2M tester (4) and the measuring system: Spraytec particle analyzer (3) from Malvern, computer and monitor (5). The atomizer (1) and Spraytec (3) were placed in a fume cupboard, and a fuel droplet absorber (6) was mounted along the spray axis. The dimensions of the atomizer nozzle: $d_o = 0.34$ mm and $l_o/d_o = 4$.

The structure of a fuel spray in atmospheric air was determined using a Malvern-made Spraytec particle analyzer, serial number MAL 1057129, equipped with an optical system for measuring the droplets in the range from 0.1 to 900 μm. The analyzer uses the laser diffraction method, which involves the measurement of scattered light intensity distribution during the passage of parallel laser beam through the spray. Thanks to the provided software the user can obtain and register values of standard parameters (SMD, volume concentration Cv) and other derivatives, i.e. arithmetic or geometric standard deviations of droplet distribution.

The diesel oil used in the tests had the following physical properties: viscosity at 40°C, 3.80 mm$^2$/s, density at 15°C, 0.8364 g/cm$^3$ and surface tension at 20°C, 28.20 mN/m.

Diesel oil was atomized using a piston pump (PRW 2M tester for the control of injector opening pressure) in the air at atmospheric pressure. The pressure of injector opening was 30 MPa.

The measurements of droplet size distribution were made in eight selected cross-sections of the spray. The experiment was repeated six times for each cross-section. The sampling frequency in the spray cross-section was 1kHz. The values of individual measurements were recorded in the specified files, a basis for subsequent accurate analysis.

## 2. The results

The mean sizes of droplet diameters for different cross-sections of the spray obtained on the Spraytec are shown in Tab. 1, the graphic representation of the experiment is shown in Fig. 2.

SMD values in individual cross-sections are the arithmetic mean of six measurements. Each single measurement used in arithmetic mean calculations was an averaged value from the period of injection. The spectrum of SMD distribution on the spray length is shown in Fig. 2.

It should be noted that in the laser diffraction method, used in the tests, the size of droplets is determined by calculating the diameter of spheres of the same volume as measured aerosol droplets, regardless of

**Table 1. SMD values [μm] in selected cross-sections of the fuel spray**

| No of measurement | Spray cross-section distance to atomizer hole | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 8 mm | 18 mm | 28 mm | 38 mm | 52 mm | 82 mm | 112 mm | 140 mm |
| 1 | 78.56 | 62.1 | 61.85 | 58.59 | 53.54 | 47.93 | 42.51 | 42.29 |
| 2 | 69.19 | 59.29 | 62.45 | 66.23 | 61.24 | 45.16 | 43.25 | 38.26 |
| 3 | 70.27 | 135.6 | 76.37 | 70.17 | 53.26 | 50.26 | 41.84 | 32.47 |
| 4 | 67.94 | 58.81 | 68.62 | 58.17 | 57.91 | 44.55 | 41.98 | 39.21 |
| 5 | 60.43 | 60.57 | 65.13 | 64.16 | 50.84 | 43.55 | 42.28 | 38.23 |
| 6 | | 55.4 | 65.69 | 67.33 | 44.6 | 43.43 | 49.8 | 38.48 |
| MEAN | **69.28** | **71.96** | **66.69** | **64.11** | **53.57** | **45.81** | **43.61** | **38.16** |

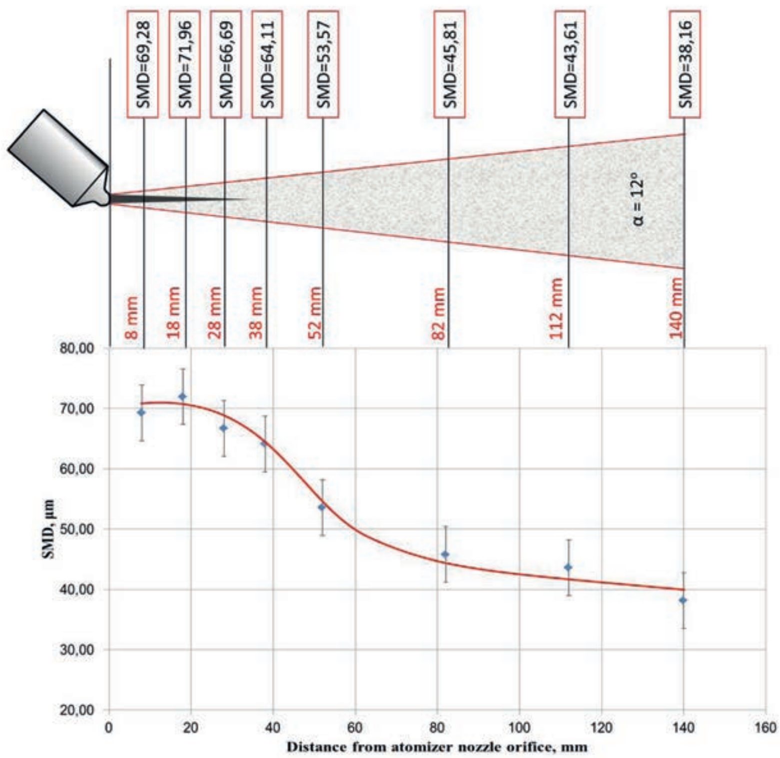


**Fig. 2. SMD in a spray depending on the distance from the atomizer nozzle orifice, $p_{oinj}$ = 30 MPa**

their actual shape. The basic granulometric distribution is therefore based on volume, and not on the size of the observed set, which is theoretically justified in a situation where SMD is the decisive parameter. A distribution analysis made by the Spraytec software is dictated by arbitrarily chosen working ranges of the diameters. The discrete distribution of diameters results from the optical resolution optimised by matching the range limits to the shape and spatial distribution of the detectors. The final results of measurements, including granulometric distribution and selected derivative parameters sum up the fractions of the basic volumetric distribution in arbitrarily quantified working ranges.

Tab. 2 and Fig. 3 display a set of measuring points of volume concentration Cv of the spray as a function of injection time, in the spray cross-section 112 mm from the atomizer hole edge, registered by the Spraytec analyzer.

Fig. 4 presents a change in SMD values during injection, in a cross-section located 112 mm from the atomizer hole edge, registered by the Spraytec particle analyzer.

**Table 2. The values of the volume concentration Cv, SMD and standard deviation of measurements in the 112 mm cross section**

| Test no | Avg Cv | STD Cv | Avg SMD | STD SMD | Avg SMD (1–2 ms) | STD SMD | Avg Cv (1–2 ms) | STD Cv |
|---|---|---|---|---|---|---|---|---|
| | Ppm | ppm | µm | µm | µm | µm | ppm | ppm |
| 112.1 | 721.2 | 175.5 | **42.51** | 21.41 | **67.45** | 7.168 | 1114 | 114.5 |
| 112.2 | 759.2 | 159.2 | **43.25** | 23.89 | **74.77** | 9.845 | 1139 | 140.9 |
| 112.3 | 744.7 | 186.9 | **41.84** | 19.48 | **59.74** | 8.777 | 1035 | 314.2 |
| 112.4 | 732.1 | 172.5 | **41.98** | 21.73 | **56.85** | 7.209 | 1113 | 226.3 |
| 112.5 | 767.6 | 179.8 | **42.28** | 22.14 | **52.13** | 4.558 | 983 | 183.0 |
| 112.6 | 703.7 | 178.8 | **49.80** | 18.44 | **87.95** | 7.274 | 1261 | 163.7 |
| | | MEAN | **43.61** | **21.18** | **66.48** | **7.472** | **1108** | |

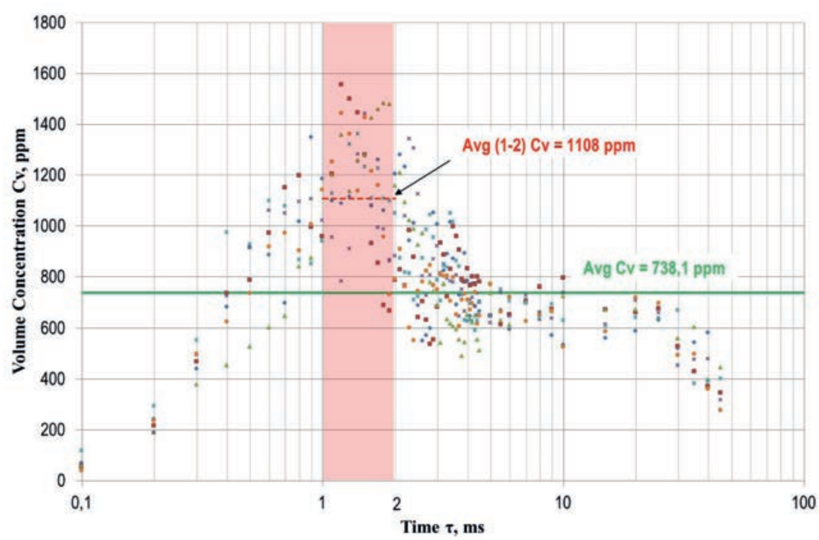


**Fig. 3. Variability of the volumetric concentration Cv during the injection in the cross-section located 112 mm from the atomizer nozzle orifice**

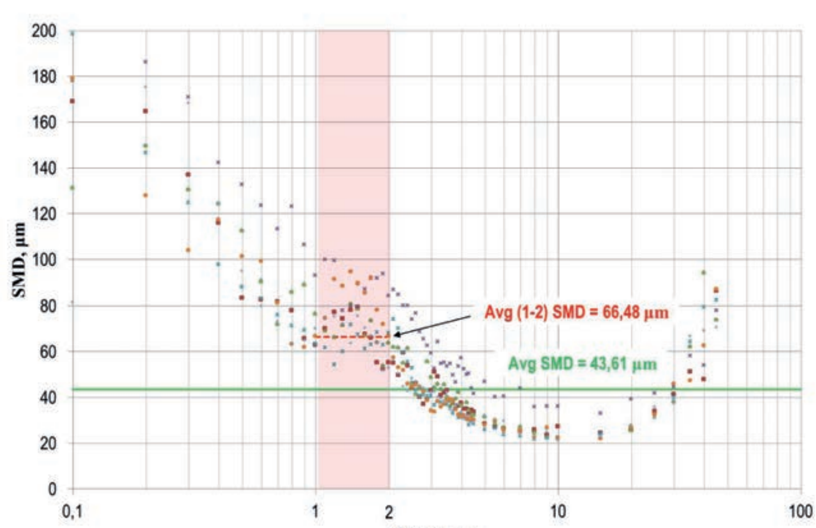


**Fig. 4. SMD variability during the injection in the cross-section located 112 mm from the atomizer nozzle orifice**

SMD values depend on the distance of the cross-section from the atomizer hole. The greater the distance, the smaller diameters of the droplets. Once the droplets cross the distance of 112 mm, their diameters stop changing. Fig. 2 illustrates stages of fuel jet atomization and spray formation. The changes of SMD along the spray axis correspond to the results available in the publications cited.

Instantaneous values of the volumetric concentration Cv change during the injection. In the conditions of the described experiment there is a clear maximum falling on the time axis between 1st and 2nd millisecond of measurement (Fig. 3). The average Cv during this period is more than 50% higher than the average for fuel atomization measurement time. For the maximum Cv the SMD value is higher by approx. 50% than the mean SMD for the whole atomization period of measurement.

The span of SMD size for the measuring range covering the atomization of the whole fuel charge leads to a large standard deviation. It oscillates around 50%. However, in the time limited to maximum Cv values and corresponding SMDs it oscillates around 10% (see Tab. 2).

## 3. Discussion

The results relate to the atomization of diesel oil in the air at atmospheric pressure by means of a typical diesel engine injector and a classical injection pump. On the basis of long term tests and operational experience the authors conclude that the quality of fuel atomization in this type of installations is dependent on a number of design and performance factors [1, 16–19]. The impact of some of these factors is partially eliminated by the common rail system.

The adoption of SMD values from the spray life period based on the presented test results gives a lower value compared to SMD in the 1–2 ms interval, where in the greatest concentration the droplets was larger by about 50% (Tab. 2). It seems purposeful to adopt as a representative value those SMDs that occur in the area of the greatest part of fuel dose (Cv max) just because the quality of combustion process, relies on the breakup of the main portion of fuel, not on the sizes of single droplets.

Since instantaneous values of Cv and SMD in a fuel spray are different depending on the position on the time axis $\tau$, it will be justified to examine fuel atomization for the following cases:

- The changes of instantaneous values of Cv and SMD for various fuel feed systems, including classical and common rail solutions.
- The changes of instantaneous values of, first of all, Cv and SMD, in various cross-sections.
- Changes of instantaneous values, above all, Cv and SMD, for various values of air pressure, in simulated conditions of the combustion chamber.

Based on these tests and their results, we should verify the validity of analyzing instantaneous values of Cv and SMD for various fuel feed systems, because the character of changes in the concentration Cv can be different for common rail fuel systems. In such cases, the methodology of determining SMD may also differ depending on the fuel feed system.

## Conclusions

To ensure the consistency of the results of measuring the quality of liquid atomization by various atomizers we require an appropriate methodology. It should be adequate for the measuring instrument and the optical model used in such instrument, describing the relationship between the diameter of particles and the manner of light diffusion. Accuracy, repeatability and reproducibility of measurements are important features of the instrument. Spraytec manufacturer declares accuracy based on latex standards NIST (deviation less than 1% for Dx (50)), but the individual particles of calibration powders have shapes similar to a sphere. In the actual spray, especially in the phase of the primary fuel jet break-up near the orifice, presence of the liquid jet and shapes of breaking away from its surface differ from the ideal shape of a drop. For this reason, the optical model used in the instrument or the algorithm of multiple scattering may have an impact on the droplet size determination.

It is also important to precisely maintain geometrical parameters of the measurement system, the spray axis relative to the axis of the laser beam and the distance from the element measuring dissipated light. These factors critically affect SMD and volumetric concentration Cv [6].

For these reasons, the development of a methodology for the determination of SMD in a spray for the largest volume concentration Cv requires research, accounting for the different parameters of atomization, primarily in a manner that will permit to utilize them in different conditions of the diesel engine combustion chamber.

The distance of the spray cross-section from the atomizer hole should be adopted on the basis of the changes in SMD values. The measurement cross-section should be outside the zone of liquid fuel jet and should be located in the area of stable SMD.

Knowing the parameters of, inter alia, droplet diameter in a fuel spray is essential at the design of combustion chambers and later in the process of controlling fuel oil supply to diesel engines. The positive effects include engine efficiency, specific fuel consumption, emissions of harmful exhaust gas components and the cleanness of the combustion chamber.

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