Bitlis Eren Üniversitesi Fen Bilimleri Dergisi

BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 11 NO: 2 PAGE: 544-552 YEAR: 2022
DOI: 10.17798/bitlisfen.1054623

Determination of Gasoline Atomization Quality under the Sinusoidal Inertial Forces with Image Processing Method

Burak TANYERİ[1], Orhan ATİLA[2], Ukbe Usame UÇAR[3*], Cengiz ÖNER[4]

[1,3]Civil Aviation High School, Aircraft Airframe-Engine Maintenance, Fırat University, TURKEY
[2]Dept. of Elec. and Elec. Eng., Faculty of Technology, Fırat University, TURKEY
[4]Automotive Engineering, Faculty of Technology, Bingöl University, TURKEY
(ORCID: 0000-0002-3517-9755) (ORCID: 0000-0001-7211-913X) (ORCID: 0000-0002-9872-2890)
(ORCID: 0000-0002-3278-2831)

Keywords: Atomization quality, Droplet size, Sinusoidal intertial forces, Gasoline direction injection

Abstract
The atomization quality has gained importance with the used of injection systems in internal combustion engines. The atomization quality has been increased by raising spray pressures by the way advances in the production technologies of high-pressure pumps and injectors. In the current situation, the spray pressures in Gasoline Direct Injection (GDI) technology have been reached bar levels between 200 and 800. When the pressure level is raised higher than the specified pressure value, the atomization quality is not provided a significant improvement and the production cost increase due to the technology required for high pressure. In this paper, the fuel has been atomized by using Sinusoidal Inertial Forces (SIF) as another method to improve the atomization quality. In the literature, there is no any study regarding the suitability of using by atomized under SIF of the gasoline fuel used in internal combustion engines. In the application study, the gasoline fuel has been atomized without the pressure by manufactured SIF generator and the droplet images obtained analysis result has been examined by using the image processing method. According to analysis results, it has been observed that the droplets sizes (around 11 µm) produced with SIF method were similar results to the droplet sizes (8-14 µm) founded using the GDI method. In addition, it was determined that the amount of atomized through the piezoelectric ceramic material in one minute was 380 ml/h. It has been determined that the smaller droplet sizes can be obtained with lower costs without using pressure thanks to this method and the method can be applied efficiently in internal combustion engines.

1. Introduction

In the internal combustion engines (ICEs), spray quality is one of the most important parameters. If it considered that it is used to aircraft, vehicles, and sea vehicles, it can be seen to play an important role in the solve the problems of the energy crisis and environmental pollution [1]. Nowadays in the used spray methods which the latest technology, the fuel is injected as primary atomization and secondary atomization process into the cylinder [2]. The secondary atomization is very effective on combustion efficiency and emission performance since it determines of droplet size, spray penetration, distribution of droplet, air-fuel rate, homogenous of the mixture, and evaporation rate of fuel [3]. Therefore, it is very important to understand the mechanism of the secondary atomization for the energy-saving and emission reduction of the ICEs. There are many studies on the development of secondary atomization in the literature. These studies are mainly attributed to the instability of gas-liquid interface decay waves, including Kelvin-Helmholz (KH) instability and Rayleigh-Taylor (RT) instability

*Corresponding author: *uuucar@firat.edu.tr*
Received: 07.01.2022, Accepted: 22.03.2022

[4]–[6]. As we know, any periodic function can be represented by the sine and cosine series through the Fourier transform. Therefore, it is important to study the droplet as the first step in illuminating a drop's secondary atomization mechanism under time-dependent acceleration. Faraday instability is used in the field of Hydrodynamics to explain the deformation and atomization process under the sinusoidal inertia force and observes the vibrations caused by vertical waves on the horizontal liquid layer surface [7]. Ultrasonic atomization with a high applied frequency is a typical application of the Faraday technique, and the effects of frequency on liquid have been experimentally studied by Lang [8], Rajan, et al [9]. Sinusoidal intertial forces used in many technical operations such as a clinical nebulizer, surface coating, humidifier of ambiance, liquid fuel sprays in the industry. Firstly, ultrasonic atomization discovered by Wood and Loomis was researched for many decades. Nevertheless, there is no general consensus on the underlying mechanism of droplet formation. There are currently two hypotheses [8]. The first hypothesis is the cavitation hypothesis. In this hypothesis, ultrasonic energy creates numerous microbubbles from nucleation, growth, and subsequent explosion in the liquid layer on the vibrating surface. Due to the cavitation randomly, mist size in the liquid column occurs randomly. The second hypothesis is capillary wave hypothesis. In this hypothesis, mist generation occurs when unstable oscillations tear the peaks of capillary waves away from the bulk liquid. Therefore, the droplet size of the generated mist depends on the wavelength of the capillary waves [10]. Faraday technique is a new research method used in the literature to explain the mechanism underlying atomization formation in this field. Although there is a limited number of research on this subject, Fushui Liu et al. Revealed an experimental study [11]. In the study, they revealed the effects of frequency, liquid amount, surface tension, and liquid density on atomization. The most important parameter used to evaluate air/fuel mixture quality is the Equivalence Ratio (ER) in internal combustion engine. The higher fuel injection pressure is both more uniform ER and faster evaporation of fuel droplets in the cylinder [12-14]. When the GDI technique is used beginning, the operating pressure of fuel injection was 50-100 bar [15]. Over the last decade, the injection pressure of the GDI technique is increased up to 250-800 bar due to recruitment better of fuel atomization [16]. The fuel injection pressure is expected that will increase to 1000 bar by 2025, as the reduction in the size of the fuel droplets increases the surface area required for the oxygen reaction [17]. To increase the pressure a lot of costly mechanical operations are required (smaller nozzle holes, higher pressure pump technology) [18].

Sinusoidal inertial force effect, which is used as an atomization method without requiring high pressure, it can create a new solution in this field to reduce both droplet size and engine production costs. There are no researches about the effect on engines of sinusoidal inertial forces approaches that will be alternative for fuel injection systems used jet nozzle in an internal combustion engine in literature. This study will contribute to the literature by determining the atomization quality of gasoline under sinusoidal inertial forces. In this paper, includes an experimental study to atomize gasoline fuel, which is a petroleum based fuel, under sinusoidal intertial forces and to determine the atomization quality by image processing method.

2. Experimental Setup and Method

In this experiment, a frequency generator circuit was set up to generate sinusoidal intertial forces, and vibration was obtained by sending a frequency of 400 kHz to piezoelectric transducers through these circuits. An imaging system was set up and an experimental setup was set up to ensure that the micron-sized droplets to be formed later were displayed.

2.1. Ultrasonic Generator Circuit

The ultrasonic generator (figure 1) is primarily designed in the experimental setup. "12-V 72A" a battery (which can be used in automobiles), switching circuits, amplifiers, and frequency circuits were manufactured for a 180 W generator capable of producing 400kHz frequency.

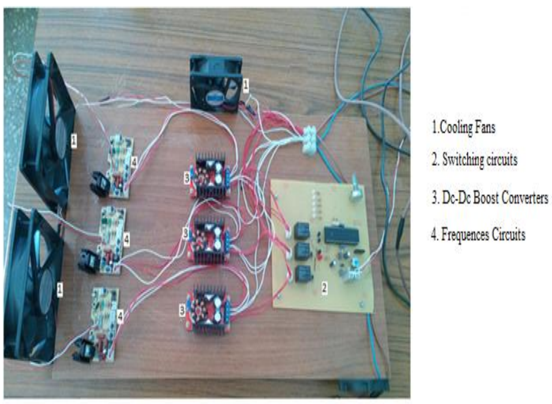

Figure 1. Ultrasonic generator circuit components

12V Dc voltage was applied to the system from the input socket, with the switching circuit of the system ready for an operation soon after. This actuating process is performed by a microprocessor directing the switching circuit, functioning the on-off switch to the open position. For this process, a relay circuit controls the voltage of the accumulator battery. The activated relay applies the battery voltage to the input socket of the converter circuit. The converter circuit voltage is raised to 30v (as previously adjusted) and sent to the pre-set frequency circuits. In the frequency circuits, the 30 V Dc voltage converts to 400 kHz signals. In the studies conducted in the literature, the effects of frequency values between 200 kHz and 2400 kHz on the droplet diameter were investigated and it was observed that the droplet diameter decreased as the frequency increased. In this study, the frequency value that can produce the same droplet diameter was chosen based on the droplet diameter of the compared GDI injector [25].This signal is also sent to the piezoelectric ceramic transducers. So these transducers generators mechanic vibrations that are converted into sinusoidal waves.

2.2. Photographing Elements and Experiment Setup

The photographing experiment setup developed for this paper has been shown figure 2 and 3. According to this setup, a high-resolution digital microscope has been used to determine the size and distribution of the droplets produced by the ultrasonic atomizer. A microscope with 20x50x200 magnification can easily view micron-sized droplets. Then the images taken are analyzed using an image processing method and droplet sizes can be calculated.

After atomization is formed in the experiment set up with gasoline fuel in a closed volume, the droplets in the liquid-gas interface move at a speed of almost zero in an environment where there is no air circulation. Droplets are displayed with ambient lighting and microscopic video capture, and the droplet size is measured by processing photo frames taken from the video.

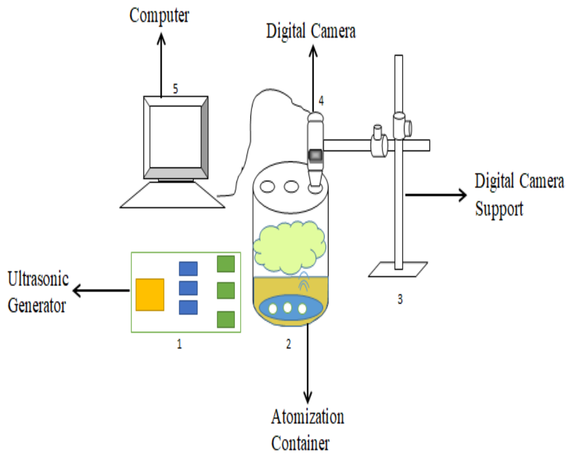

Figure 2. Schematic imagine of photographing experiment setup

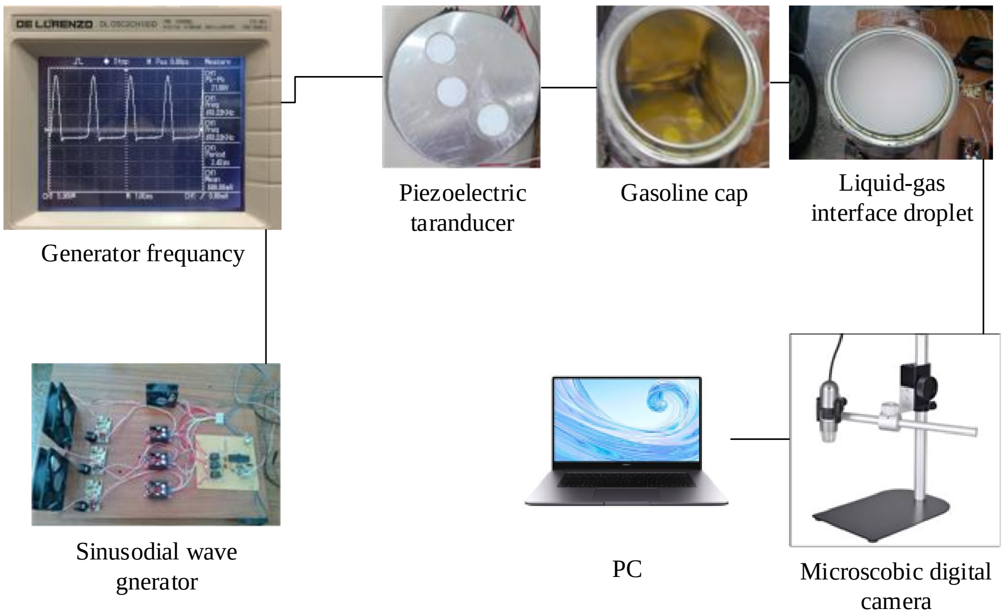

Figure 3. The photographing experiment setup

2.3. Image Processing

Image processing includes converting an image to digital and filtering enhancement, segmentation, pattern extraction, pattern recognition, feature extraction etc. on this image. Digital image processing methods have two main goals. These purposes are to improve the image so that the image can be interpreted better and to analyze the image so that the computer can interpret the image. In this paper, all image processing and feature extraction operations were conducted in a MATLAB environment.

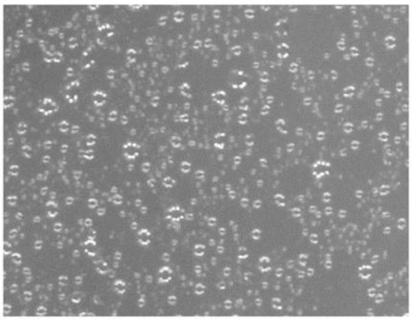

Figure 4. Original Image

The photograph in figure 4 shows image obtained from the microscope in the experiment setup that is shown in figure 2. The sound waves piezoelectric ceramic transducer produce cause the breaking of the droplets from the surface of the liquid fuel. The broken droplets fill the empty volume of the atomization container and move with a speed close to zero. Meanwhile, the digital microscope cameras immersed from three different points in fog cloud display the droplets by taking photograph and video. The obtained image has been analyzed using the flow chart in figure 5. Afterwards, this picture has been transformed to a black-white image (figure 6) by the way image program.

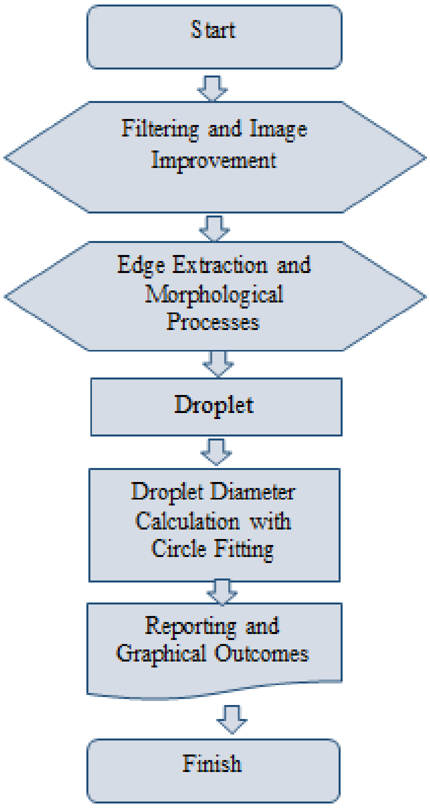

Figure 5. Image Processing Flow Chart

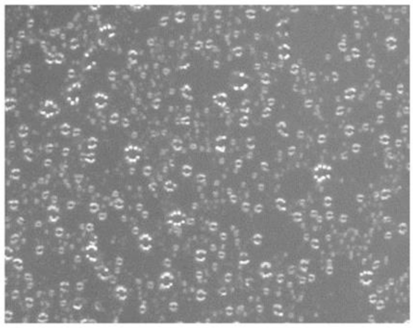

Figure 6. Improved image.

Image enhancement process has been applied on the raw image using the edge reinforcement filter for distinguish from the background more easily and to make a more accurate segmentation of the patterns in image before segmentation. Then the image has been segmented through morphological processes and edge removal methods. The Canny Edge Detection Method was used to segment the droplet images taken from the microscopic camera. The Canny Edge Detection that is a method we used utilizes as a threshold level. The Canny Algorithm preserves all edges that are above the threshold level while ignoring all the edges whose edge strength is below the threshold level. In this study, we used the regional optimum thresholding method (otsu) to determine the edge threshold level. The optimum threshold value method calculates a value called in-class (foreground and background pixels) variance for all possible thresholds and finds the index at which this value is the lowest [19].

In the proposed algorithm, firstly G_x and G_y spatial gradients are calculated and an edge strength matrix [G] is found. Then, the edge pixels E are determined according to the threshold level(th_level) obtained previously.

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$G_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

$$\lceil G \rceil = \sqrt{G_x^2 + G_y^2} \qquad \text{Eq. 1.}$$

$$E = \lceil G \rceil > th\_level \qquad \text{Eq. 2.}$$

After the segmentation process, it is performed labelling process which each droplet pattern has an identity. Later size information of each droplet pattern is calculated and it is saved in its own label. The segmented image and labelled droplet patterns are shown in figure 7.

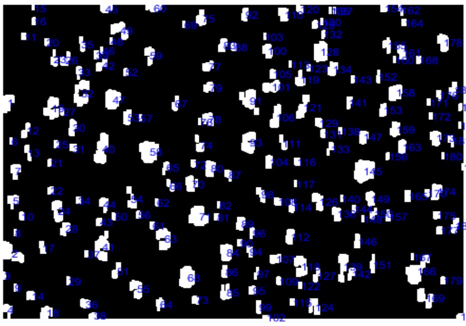

Figure 7. Segmented and labelled Image

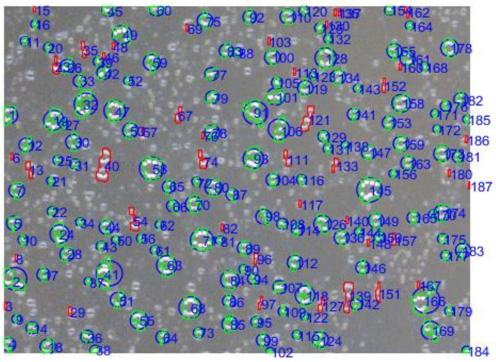

Figure 8. Calculation of droplet diameter with circle fitting method

As a result of atomization, the circle fitting method has been used to calculate the size of the fuel droplets that take a shape similar to water spheres. Fuel droplets cannot take a full circle shape due to discontinuities and incorrect mergers in the patterns obtained as a result of edge extraction and segmentation processes. On the other hand, when obtained images with a digital camera have been examined, it has been observed that a light ring has consisted around the droplets due to reflection of the LED light source in the camera. These situations cause incorrect calculations of the sizes of the droplets. In this study, we propose the circle fitting method to deal with this situation. Thus, the best circle that fits the boundaries of the existing droplet patterns will provide us with the actual size of the droplet. When this method is applied to all droplet patterns in the image taken from the camera, the sizes of all droplets can be calculated. Patterns that cannot be obtained as droplet shape as a result of incorrect segmentation are ignored and not included in the size calculation process.

According to Figure 8, patterns that have been marked with red colour have been ignored for giving false information because they are not segmented correctly.

2.3.1. Morphological Operations

Morphological image processing is non-linear operations related to the shape or morphology of features in an image. Morphological operations scan an image with a template called a structuring element. The structuring element is positioned at all possible locations in the image and it is compared with the corresponding neighbourhood of pixels. Erosion and dilation are among the most commonly used techniques from morphological operations. The erosion operation test whether the element fits within the neighbourhood, while the dilation operation test whether it hits the neighbourhood[20].

The binary dilation of F by S, denoted F⨁S, is defined as the set operation:

$$F \oplus S = \{z | \hat{S}_z \cap F \neq \emptyset\} \qquad \text{Eq. 3.}$$

where $\hat{S}$ is the reflection of the structuring element S. In other words, it is the set of pixel locations z, where the reflected structuring element overlaps with foreground pixels in F when translated to z.

The binary erosion of F by S, denoted F ϴ S, is defined as the set operation.

$$F \ominus S = \{z|S_z \subseteq F\} \quad \text{Eq. 4.}$$

It is the set of pixel locations z, where the structuring element translated to location z overlaps only with foreground pixels in F. n this study, 4x2 rectangular and 2x2 square structural elements were used respectively for dilatation and erosion operations.

2.3.2. Circle Fitting

Consider n sample points (x_i, y_i). (i=1,…,n) which are fitted by a circle of radius R at the center (x_o, y_o). The geometric distance of a sample points from the center of the circle is indicated as,

$$R^2 = \sqrt{(x-x_o)^2 + (y-y_o)^2}$$
$$x^2 - 2xx_o + x_o^2 + y^2 - 2yy_o + y_o^2 \quad \text{Eq. 5.}$$

If the equation is converted to matrix format

$$[-2x \quad -2y \quad 1][x_o \quad y_o \quad -R^2 + x_o^2 + y_o^2]' = -[x^2 + y^2] \quad \text{Eq. 6.}$$

The expression is to be rearranged

$$A=[-2x \quad -2y \quad 1]\,,\ B=-[x^2 + y^2]$$
$$D = A^{-1}B \quad \text{Eq. 7.}$$

to obtain x_0, y_0 and R

$$x_0 = D_{11}, y_0 = D_{21} \ and\ R = \sqrt{{x_0}^2 + {y_o}^2 - D_{31}} \quad \text{Eq. 8.}$$

2.3.3. Elimination of Incorrectly Measured Droplets

As seen in the microscope images, some droplets are very close and overlapped. This causes incorrect segmentation when separating the droplets. As a result, droplet sizes are measured incorrectly. The areas of the droplets calculated after the segmentation process and the areas of the calculated droplets after the circle fitting process are different. The difference between these areas calculated for each segment was controlled with a certain threshold level, and the droplets that were measured incorrectly were eliminated.

$$err_1 < \frac{|A_s - A_c|}{A_s} < err_2$$
$$A_s = S_i \quad \text{Eq. 9.}$$
$$A_c = \pi R_i^2$$

where A_s is droplet area calculated after segmentation S_i, $A_c$is droplet area obtained by fitting the circle after segmentation and err_1 and err_2 are threshold levels. err_1 and err_2 values were accepted as 0.2 and 2 respectively in this study.

3. Results and Discussions

This study was carried out to determine whether there is an alternative atomization method to the fuel injection system in spark-ignition engines by atomizing the gasoline fuel used in internal combustion engines under sinusoidal intertial forces and by measuring the atomization quality by image processing method.

Lang [21], who conducted research on ultrasonic atomization, presented an equation that calculates the change in the average droplet diameter depending on the frequency by making a correlation.

$$d_m = C.2\pi\left(\frac{\sigma}{\rho}\right)^{\frac{1}{3}}.\left(\frac{2}{2\pi f}\right)^{\frac{2}{3}} \quad \text{Eq. 10.}$$

Here C = 0.35 ± 0.03 constant number, σ is surface tension constant and ρ is the fluid density. σ and ρ are constants for a given fluid. In Equation 10, it can be seen that the 2/3 power of the independent variable f is a power function. The density of the gasoline used in the fixed frequency experiment was 737.5 kg / m^3 [22] and the surface tension of 2.21x10-2 N/m^1 was found to be 5.76 µm when applied to the Lang equation. Considering that there is a measurement coefficient in the Lang equation, it is concluded that the experimental results are close to the theoretical calculations.

The droplet size and volumetric distribution of atomization in gasoline experiments conducted at a frequency of 413 kHz have been indicated in figure 9.

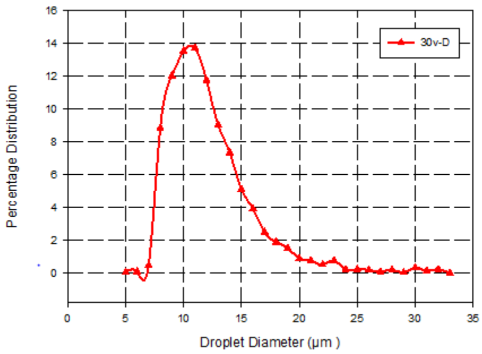

Figure 9. The volumetric distribution of droplet size

When figure 9 is examined, it is seen that the diameter of the droplets formed in the ultrasonic atomizer varies in the range of 5-33µm. In terms of volume, the most obtained droplet diameter is between 11-12 µm. When the examination of figure 10, the droplet performance of a piezo-driven injector with 200 bar spray pressure are similar to the droplet size of ultrasonic atomization examined in this study [24].

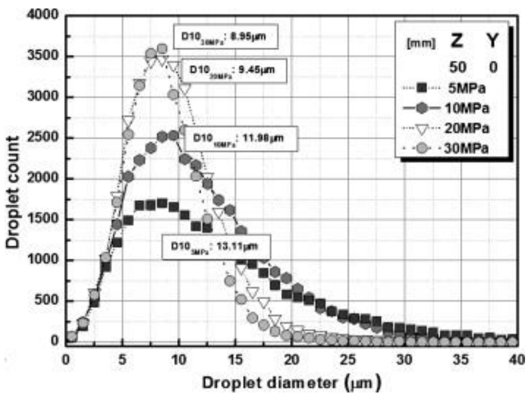

Figure 10. GDI Injector atomization quality[24]

Wadekar et al. [17] conducted a numerical study and studied the change of droplet size with pressure on a jet nozzle in Fig. 11. According to the results of the study, as the pressure increases, the droplet sizes within the determined volume decrease. When the droplet size-volumetric distribution graphs of both experimental jet nozzle studies and numerical jet nozzle studies are examined, it is seen that their tendencies are similar. In this study, a similar graphic was observed too. Therefore, it is thought that this atomization method can be used in internal combustion engines.

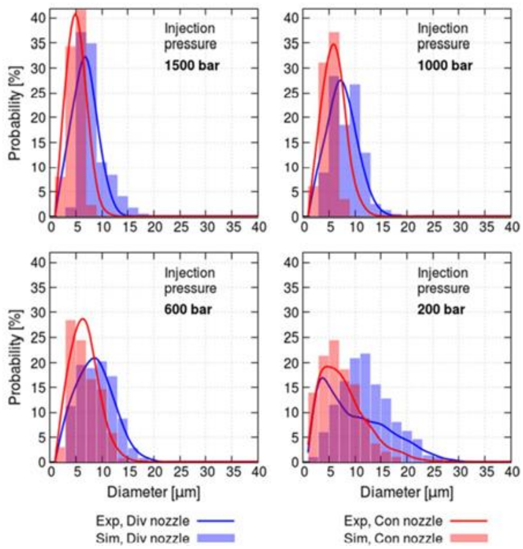

Figure 11. Comparison between measured and calculated droplet size distribution for the divergent and the convergent nozzle at 200, 600, 1000 and 1500 bar injection pressure [17].

In this paper performed under sinusoidal intertial forces, both the size of the droplet and the trend of the graph have shown similar results with the jet nozzle. According to the pressure increase in numerical and experimental studies realized on the jet nozzle, it is found that dwindling in droplet size is not remarkable. Besides, pressure increase methods have serious manufacturing difficulties and costs. In the method of atomization of the droplets with sinusoidal intertial forces, it has been determined that droplet sizes can be reduced to nano sizes without using pressure. In this respect, it has been observed that the atomization method with sinusoidal intertial forces is superior to pressure systems in terms of both production cost-manufacturing ease and operating performance.

4. Conclusions

In this paper, atomization has been performed using piezoelectric ceramic disc material and creating a sinusoidal inertial force on gasoline fuel. This atomization has been processed with image processing method by photographing through microscopic cameras and the sizes of droplets have been calculated. The sizes of droplets and their distribution have given similar results to GDI injector used in spark ignition engines. In the literature, it is seen that the droplet size distribution formed by the GDI injector at different pressures varies between 1-40 µm, and the volume of the highest amount of droplets is in the range of 8-14 µm depending on the pressure. This paper, in the results of the experiments conducted under sinisodial intertial forces, it is seen that the droplet sizes vary between 1-35 µm and the highest volume of droplets is around 11 µm at unpressurised. Therefore, it can be said that the quality of the atomization made without using any pressure is sufficient. Since the SIF method is independent of pressure, it does not need a pressure pump, allows the droplet diameter to be controlled depending on the frequency of the sinusoidal wave formed, and is less costly than a pressure pump. As a disadvantage, the pressure pump cannot be deactivated since the ignition is provided by injection in compression ignition engines.

Also, the amount that a piezo electric ceramic material atomizes in per minute has been measured as 380 ml/h. This value is important to calculate how many sinusoidal wave generators should be used for fuel injection system of internal combustion engines. It has been found that gasoline atomization quality is suitable for spark ignition engines when both droplet distribution and size of droplet are considered. An alternative injection system to the fuel injection system of internal combustion engines can be produced using sufficient sinusoidal wave generators and it can be done scientific researches on fuel consumption and emission values of this system.

In future studies, using optimization methods, engine performance experiments can be performed by determining the ideal fuel amount required by the engine according to cycle and load conditions and creating a sufficient number of piezoelectric ceramic transducer modules.

Contributions of the authors

Dr. Lecturer Burak TANYERİ:	Conceptualization, Methodology, Software, Application
Res. Ass. Orhan Atila :	Methodology, Software, Application
Dr. Ukbe UÇAR:	Writing – Literature Review & Editing, Visualization
Prof. Dr. Cengiz: ÖNER	Writing – Literature Review & Editing, Visualization

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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