Proceedings of the Seventh Fuel and Combustion Conference of Iran
Feb. 13 - 14, 2018, Sharif University of Technology, Tehran, Iran
FCCI-2018-1126

Experimental and numerical study of spray characteristics of modified bio-diesel in various fuel and ambient conditions

A. R. Ghahremani
Center of Excellence in Energy Conversion, School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran. P.O.Box: 11155-9567

M. Saeedan
School of Mechanical Engineering, University of Tehran, Tehran, Iran

M. H. Saidi
Center of Excellence in Energy Conversion, School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran. P.O.Box: 11155-9567

Abstract
In this research, a new combination of bio-diesel, molasses bio-ethanol, and water has been explored. This combination is called Modified Bio-diesel Fuel (MBF) and can be used instead of fossil fuels. To have better insight, macroscopic and microscopic behaviors of MBF spray have been studied. In comparison with fossil fuels, MBF is better at emissions and production cost. Moreover, high cetane number and oxygen content make MBF an interesting fuel in internal combustion engines. Ohnesorge number and Sauter Mean Diameter (SMD) as atomization characteristics have been investigated by applying two-phase Eulerian–Lagrangian approach in CONVERGE software. Employing droplets atomization physics and dimensional analysis, Atomization Index (AI) that is the ratio of square of inertia forces to product of viscous and surface tension forces has been studied as well. By means of this number, level of atomization of the spray can be estimated. Results show the indirect relation between AI number and SMD, that means increasing the AI number leads to the lower SMD and better atomization. Ohnesorge and AI numbers can determine atomization level of the spray while their results come to the same conclusion. In addition, effects of fuel and ambient temperatures on the spray have been explored and results indicate that they do not affect seriously the characteristics of spray. Due to the similarity between spray behavior of MBF and diesel fuel, it seems MBF can be used in diesel engines instead, though its combustion properties should be considered, as well.

Keywords: AI Number, Atomization, Spray Characteristics, Simulation, Modified Bio-Diesel.

1. Introduction

Emission and engine performance of diesel engines are affected by quality of air and fuel mixture. Homogeneity of the mixture enhances the engine performance and reduces the Particulate Matter (PM) emission as well [1]. Environmentalists believe that using environmental friendly fuels, bio-fuels, is one of the best choices to reduce the air pollution. Ability of using bio-diesel fuels in diesel engines almost without any modification in the fuel system makes these fuels one of the best substitutions for fossil fuels. Direct Injection (DI) systems improves atomization characteristics while reduces fuel consumption, so using these systems is noteworthy for environmental concerns. Therefore, nowadays studying on spray characteristics of bio-fuels in DI engines are ongoing [2-7].

Park and Lee [8] investigated the microscopic and macroscopic behaviors of spray of diesel fuel experimentally and numerically. They obtained SMD, tip penetration length, and spray development employing Phase Doppler Particle Analyzer (PDPA) and a visualization technique. They changed TAB break-up model to KH-DDB model in KIVA-3V code to study the spray atomization process numerically. Park et al. [9] experimentally and numerically studied spray behaviors of Soybean oil Methyl Ester (SME) as a bio-diesel fuel compared with those of diesel fuel in a diesel engine. Applying a visualization system, spray characteristics such as area, tip penetration, centroid of spray, and injection delay have been measured. The simulation was performed by KIVA-3V code and using KH-RT break-up model and the results were validated by the experiment. Park et al. [1] investigated the influences of fuel and ambient condition on spray characteristics of Soybean oil Methyl Ester (SME) fuel. They used a visualization system and the KIVA-3V code simultaneously and compared the numerical results with those of experiment. Their results indicated that increasing ambient temperature increases spray tip penetration while enhancing fuel temperature has not an important effect on tip penetration length. They showed that enhancing the fuel temperature increases the vapor mass while decreases the mean axial velocity of droplets and the number of droplets due to evaporating the small droplets. Park et al. [10] investigated the effects of ambient pressure and fuel temperature on spray of several blends of Dimethyl Ether (DME) and diesel employing the visualization system and KIVA-3V code. Their results demonstrated that tip penetration and cone angle of diesel fuel are longer and narrower than those of DME fuel, respectively. They showed that increasing the fuel temperature evaporates the DME fuel and reduces the cone angle and tip penetration as well. They also reported that at atmospheric condition the size of droplets of diesel fuel is greater than DME's. Lee and Huh [11] explored spray characteristics, combustion, and emission of blend of diesel fuel and bio-diesel (soy based) numerically. Their results showed that because of greater viscosity and surface tension of bio-diesel, spray of bio-diesel had lesser volatility and higher SMD in comparison with those of diesel fuel. Lešnik et al. [12] employing high speed imaging technique, visualized spray of a bio-diesel, namely Rapeseed oil and compared the visualized results with those of AVL Fire. Their results indicated that spray tip penetration and SMD of bio-diesel are larger than diesel's, while bio-diesel has lower spray cone angle compared with spray cone angle of diesel fuel. Vajda et al. [13] numerically studied the effect of several blends of bio-diesel and diesel fuels on spray tip penetration and cone angle that mainly affect emissions and combustion performance. They employed a number of primary and secondary break-up empirical parameters in AVL FIRE software to model the biofuels and validated the numerical results with their own experiments. Their results showed that it is possible to use bio-diesels instead of conventional diesel fuels in diesel engines.

Though there are several research studies on spray characteristics of blends of different bio-diesels and conventional diesel fuels [3, 4, 14], it seems the simultaneous effects of ambient and fuel conditions (pressure and temperature) on spray of new bio-diesels should be taking into account in detail. In this regard, microscopic and macroscopic characteristics of a new bio-diesel, i.e. MBF, have been investigated in this study. The MBF is a combination of molasses bio-ethanol, bio-diesel, and water, which behaves as a single-phase bio-diesel using an emulsifier. Using CONVERGE software the effects of pressure and temperature of both ambient gas and fuel on spray behaviors of MBF and conventional diesel fuels have been explored. Applying a high speed visualization system the numerical results have been validated by experiment. At the end, the AI number that can predict the atomization level of the injected spray, has been investigated.

2. Computational physical model

Employing two-phase Eulerian–Lagrangian approach in CONVERGE software, atomization properties of the abovementioned fuels have been computed. Applying a novel cut-cell Cartesian technique for grid generation, the mass, momentum, and energy equations have been computed simultaneously. Based on experimental test rig, a cylinder with the radius and length of 40 mm and 120 mm respectively, have been modeled in CONVERGE using base grid size and total cell number of 0.9 mm and 850,000 respectively. Applying Renormalization Group Theory (RNG) k-ε turbulence model, the Favre-averaged Navier-Stokes is mentioned for the flow field of gas phase. Kelvin Helmholtz-Rayleigh Taylor (KH-RT) liquid break-up model has been employed to predict the injected spray break-ups. To predict collisions of droplets the No Time Counter (NTC) algorithm and O'Rourke collision model have been used investigating different collisions such as stretching, reflexive separation, bouncing, or coalescence. Using the dynamic drag model the dependency of drag coefficient with the shape of the droplets has been taken into account. For more information about the mentioned models and theories one can be study the CONVERGE theory manual [15].

3. Experimental test rig

In order to study the spray behaviors experimentally, direct injection and high speed visualization systems installed as it is obvious in Fig. (1). Employing a high-speed camera (MotionBLITZ Cube3) and a LED light source, images of the spray which is injected through the common rail and injector, have been captured. Three BK7 optical windows which are located around the combustion chamber are necessary for this capturing. Image Analyzer Pro. (IAP) is a Graphical User Interface (GUI) software, which has been developed to analyze the captured images and export the spray characteristics results.

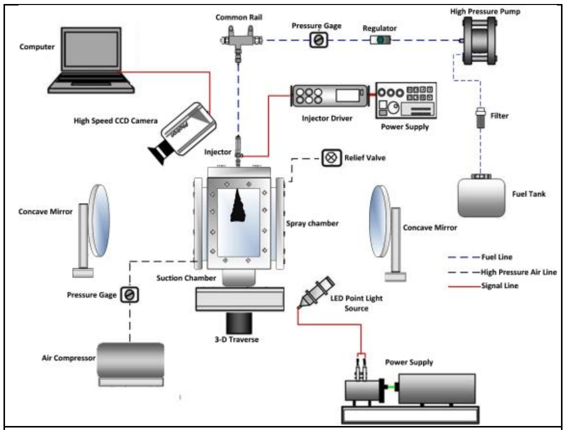


Figure 1- Schematic diagram of experimental setup.

The physical specifications of MBF and diesel fuel are listed in Table (1). Regarding to the point that these specifications are mainly affect the spray characteristics and subsequently the combustion performance and emissions, measurement accuracy of them is important for authors of this work.

Table 1. Physical specifications of tested fuels.

fuel	stoichiometric air/fuel ratio	density (g/cm^3)	kinematic viscosity (mm^2/s)	surface tension (mN/m)
Diesel	14.49	0.832	4.31	24.31
MBF	11.80	0.876	10.74	26.87

The details of experimental setup can be found in [16], therefore in this section only a brief explanation is described.

4. Results and discussion

In this section, the influences of pressure and temperature on spray microscopic and macroscopic characteristics of MBF and conventional diesel fuel have been explored. In this regard, injection and ambient pressures are varied between 200, 1000 bar and 1, 15 bar, respectively. Furthermore, ambient and fuel temperatures of 500 K and 340 K have been taken into account in addition to 300 K.

Figure (2) represents the comparison between measured and predicted spray tip penetration of diesel fuel at injection pressure of 200 bar and temperature of 300 K. As shown in this figure there is a good agreement between numerical and experimental results of the present study.

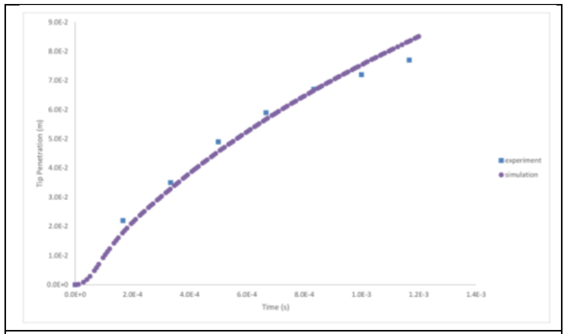
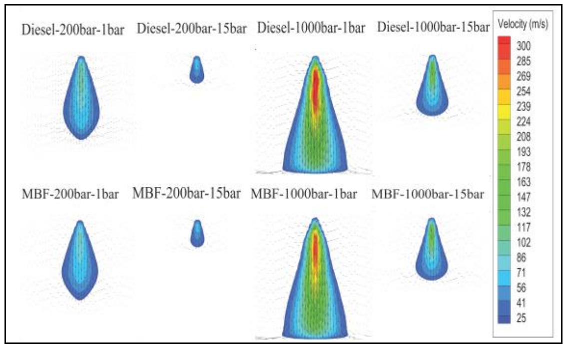


Figure 2- Predicted and measured spray tip penetration vs. time.

4.1. Spray macroscopic characteristics

Figure (3) shows the comparison between spray images of MBF and diesel fuel in different pressures and temperatures at 1.2 ms after the start of injection. The variation of colors and the size of vectors in this figure indicate the velocity magnitude of the spray. As it is obvious in this figure, the spray shape and structure of all cases are similar. Due to some vortices, mixture of fuel and ambient gas is observed in this figure. Figure (3) illustrates that when the difference of injection and ambient pressures increase the spray propagate easily and both spray velocity and area enhance, while varying the temperature has no important effect on the spray. As it is shown in Fig. (3), when injection and ambient pressures are 1000 and 1 bar, respectively, the spray penetrates more rapidly compared with the other cases and impacts to the wall. In addition, the velocity magnitudes of both diesel fuel and MBF are almost the same due to the proximity of their physical properties.



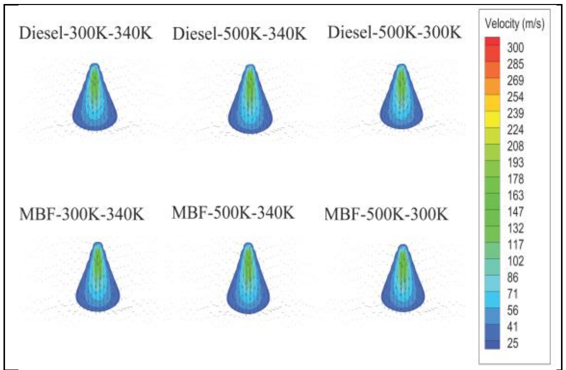


Figure 3- Spray shape of diesel fuel and MBF at 1.2 ms after start of injection.

Figure (4) depicts the variation of spray tip penetration length versus time for different conditions. Figure (4-a) shows the effects of pressure on tip penetration when the temperature of fuel and ambient are 300 K. Results show that increasing the ambient pressure, decreases tip penetration as a result of enhancing the ambient gas density which reduces the spray speed. As time passes, the difference between spray tip penetration length of both MBF and diesel fuels increases a bit slightly. Increasing the injection pressure enhances the injection momentum and leads to the higher spray tip penetration. In addition, Park et al. [9] referred to the Roisman et al. [17] and divided the spray penetrating region to the main and front edge regions. They showed that the momentum of the entrained ambient gas and the injection inertia of the spray govern the spray in the main region while in the front edge region, the governing forces are the aerodynamic drag force and the droplets inertia, as well. Fig. (4-b) illustrates the influences of temperature on the spray tip penetration progress. Increasing the ambient temperature decreases the ambient gas density and reduces the forces that prevent the spray from going forward. As shown in this figure, temperature slightly affected the spray tip penetration and increasing both fuel and ambient temperatures, increase the spray tip penetration a little. Consequently, it could be concluded that changing the physical properties of fuel and ambient gas caused by varying the temperature, do not affect the spray remarkably.

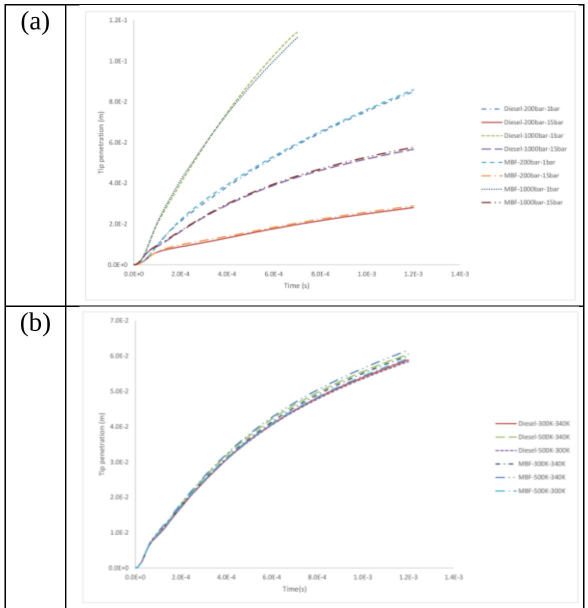


Figure 4- Spray tip penetration vs. time for different, (a) injection and ambient pressures, and (b) fuel and ambient temperatures.

Figure (5) shows the average spray cone angle of different fuels and conditions. As expected, spray cone angle enhances by enhancing the ambient pressure due to increasing the aerodynamic drag forces, which prevent the spray from penetrating forward. Moreover, increasing injection pressure increases the momentum of the spray, so spray can overcome the drag forces and penetrate easily, consequently the spray cone angle almost decreases. Because of the physical properties of MBF and diesel fuel are approximately the same, the spray cone angle of both of them are similar. As this figure reveals, variation of temperatures almost have not any important effect on the spray cone angle.

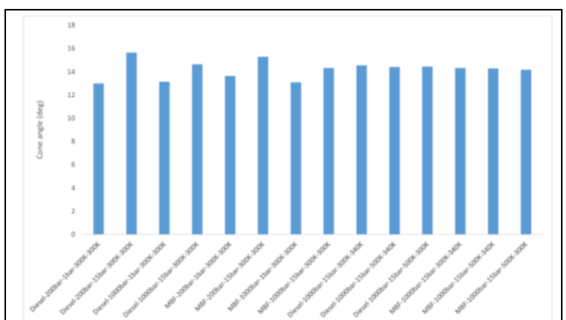


Figure 5- Average spray cone angle for different fuels and conditions.

4.2. Spray microscopic characteristics

As Park et al. [1] demonstrated, investigating the microscopic characteristics of the spray specially fuel atomization is one of the key ways of optimizing the engine performance and reducing the exhaust pollutants. In this regard, in this section the microscopic properties of the injected spray such as SMD, Ohnesorge and AI numbers will be reported and analyzed as well.

Figure (6) shows the effects of pressures on the SMD characteristics of MBF and Diesel fuels. Trend of all curves in this figure are similar and the SMD of all cases decreases when time passes until reach to an approximately constant value, although there a bit tendency to increase due to collision and coalescence of droplets. As expected increasing the injection pressure, enhances the velocity of the spray and decreases the SMD. Ejim and Fleck [18] reported that viscosity is one of the key factors which affect the SMD. So, as a result of higher viscosity, the SMD of MBF is higher than diesel's. Furthermore, because of better volatility of diesel fuel compared with that of MBF, the atomization behavior of diesel fuel is better than that of MBF. From the aspect of spray breakup, increasing the ambient pressure enhances the drag force in front of the spray droplets that advances the breakup timing and reduces the average size of droplets, while coalescence of the droplets is the other factor that affects the SMD.

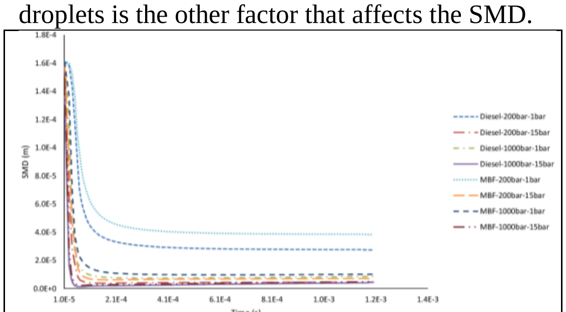


Figure 6- Sauter Mean Diameter (SMD) variation for different fuels and conditions.

Ohnesorge number which is one of the key non-dimensional numbers in determining the atomization level of the spray, is related to the viscous force to the product of surface tension and inertia forces as follows:

$$Oh = \frac{\mu}{\sqrt{\rho\sigma L}} \quad (1)$$

whereas, σ , μ , ρ , and L are surface tension, viscosity, density, and characteristic length scale, respectively.

Wu et al. [19] plotted the Ohnesorge number versus Reynolds number and divided it to the different zones which specify the atomization level of the spray. Figure (7) indicates the variation of Ohnesorge number versus Reynolds number for different test cases. As this figure shows, increasing the injection pressure increases Ohnesorge number and improves atomization criteria of the spray due to increases velocity of spray which signifies aerodynamic and turbulence forces. In addition, results show that reducing the ambient pressure boosts the atomization level as a result of decreasing the drag force. MBF viscosity and surface tension are higher than those of diesel fuel, which leads to the lower Reynolds number and higher Ohnesorge number for the same conditions. With regard to this point that variation of Reynolds and Ohnesorge numbers for MBF and diesel fuels are reverse, there is not any significant variation in atomization level of these fuels.

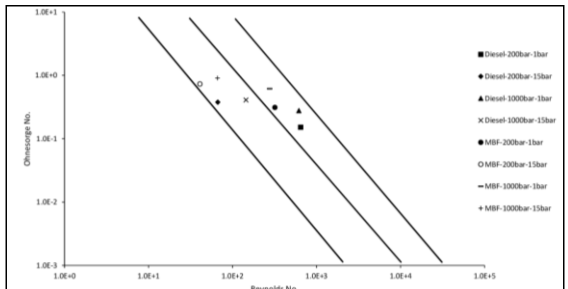


Figure 7- Variation of Ohnesorge number vs. Reynolds number for different test cases.

According to the dimensional analysis that is related to the atomization properties of spray, a new non-dimensional number has been introduced by Ghahremani et al. [20]. The atomization level of injected spray can be identified by this number. AI number can be defined by physical properties of spray (Eq. (2)).

$$AI = \frac{\rho^2 U^3 d^2}{\mu\sigma} \quad (2)$$

Regarding Eq. (2), the ratio of square of inertia forces to product of surface tension and viscous forces affects AI number and atomization behaviors as well.

Sauter Mean Diameter (SMD), which shows the mean size of the droplets of the spray, is used to study atomization behavior of the spray. SMD declines due to increasing of fluid velocity and density, and decreasing of the viscosity and surface tension of fluid, based on Ashgriz [21] and Ejim et al. [18] research. Therefore, increasing the atomization level and decreasing SMD can be inferred by increasing AI number. The average of SMD for different fuels at various injection and ambient conditions versus AI number can be found in Fig. (8).

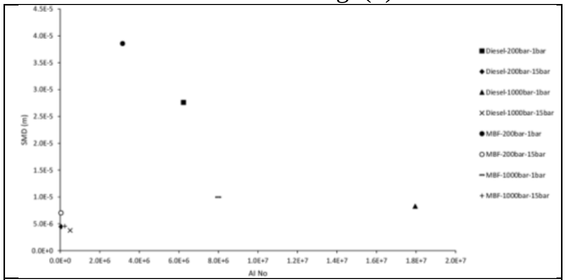


Figure 8- AI number of different fuels at various injection and ambient conditions.

It can be perceived from this figure that rising the injection pressure, increases velocity and decreases the SMD, while enhance AI number. Also, both surface tension and viscosity of the fuel avoid droplet formation and enhances the droplet diameter. So increasing injection pressure and applying the fuel with lower surface tension and viscosity, which all cause higher AI number, decrease SMD and enhance atomization behavior. As viscosity and surface tension of diesel fuel is lower than those of MBF, atomization level and AI number of diesel fuel are better than MBF. Since the results of AI number and Ohnesorge number are well-matched, they can be applied instead of each other.

5. Conclusion

In this study, macroscopic and microscopic behaviors of MBF and diesel fuel sprays have been investigated by varying the condition of ambient and injection pressures and temperatures. MBF and conventional diesel fuel can be used in diesel engines interchangeably while MBF has lower emissions and production costs yet higher cetane number and oxygen content. Employing two-phase Eulerian–Lagrangian approach in CONVERGE software, the analysis of mixture formation, atomization level, and air entrainment have been performed. Moreover, AI number has been computed in order to determine spray atomization behavior. It is found out that there is a direct relation between AI number and atomization level. To understand the spray atomization level, Ohnesorge and AI numbers have been applied that the results of both numbers verify the other. According to the results, fuel and ambient temperatures do not influence spray characteristics significantly. One of the key outcomes of the present work is that combination of MBF and diesel fuels can be used in diesel engines due to the similar characteristics of their sprays.

6. Acknowledgement

Financial support from National Elites Foundation and INSF through project No. 940017 are greatly appreciated.

References

[1] Park, S.H., Kim, H.J., Suh, H.K., Lee, C.S., "Experimental and numerical analysis of spray-atomization characteristics of biodiesel fuel in various fuel and ambient temperatures conditions", *International journal of heat and fluid flow*, **30** (5), pp. 960-970 (2009).

[2] Pan, J., Yang, W., Chou, S., Li, D., Xue, H., Zhao, J., Tang, A., "Spray and combustion visualization of bio-diesel in a direct injection diesel engine", *Thermal Science*, **17** (1), pp. 279-289 (2013).

[3] Ghahremani, A., Jafari, M., Ahari, M., Saidi, M., Hajinezhad, A., Mozaffari, A., "Spray characteristics and atomization behavior of bio-diesel (Norouzak) and diesel fuel blends", *Particulate Science and Technology*, pp. 1-12 (2016).

[4] Ghahremani, A., Saidi, M., Hajinezhad, A., Mozafari, A., "Experimental investigation of spray characteristics of a modified bio-diesel in a direct injection combustion chamber", *Experimental Thermal and Fluid Science*, **81** (pp. 445-453 (2017).

[5] Suh, H.K., Roh, H.G., Lee, C.S., "Spray and Combustion Characteristics of Biodiesel/ Diesel Blended Fuel in a Direct Injection Common-Rail Diesel Engine", *Journal of Engineering for Gas Turbines and Power*, **130** (3), pp. 032807 (2008).

[6] Ghahremani, A., Karimi, H., Saidi, M., Mozafari, A., "Letter to" A contribution to the understanding of isothermal diesel spray dynamics"", *Fuel*, **187** (pp. 468-469 (2017).

[7] Naghizadeh, M.M., Ghahremani, A., Saidi, M.H., "Numerical simulation of spray characteristics of bio-ethanol and its blend with gasoline in a direct injection combustion chamber", *Modares Mechanical Engineering*, **15** (4), (2015).

[8] Park, S., Lee, C., "Macroscopic structure and atomization characteristics of high-speed diesel spray", *International journal of automotive technology*, **4** (4), pp. 157-164 (2003).

[9] Park, S.H., Kim, H.J., Suh, H.K., Lee, C.S., "A study on the fuel injection and atomization characteristics of soybean oil methyl ester (SME)", *International Journal of Heat and Fluid Flow*, **30** (1), pp. 108-116 (2009).
[10] Park, S.H., Kim, H.J., Lee, C.S., "Study on the dimethyl ether spray characteristics according to the diesel blending ratio and the variations in the ambient pressure, energizing duration, and fuel temperature", *Energy & Fuels*, **25** (4), pp. 1772-1780 (2011).
[11] Lee, Y., Huh, K.Y., "Numerical study on spray and combustion characteristics of diesel and soy-based biodiesel in a CI engine", *Fuel*, **113** (pp. 537-545 (2013).
[12] Lešnik, L., Vajda, B., Žunič, Z., Škerget, L., Kegl, B., "The influence of biodiesel fuel on injection characteristics, diesel engine performance, and emission formation", *Applied Energy*, **111** (pp. 558-570 (2013).
[13] Vajda, B., Lešnik, L., Bombek, G., Biluš, I., Žunič, Z., Škerget, L., Hočevar, M., Širok, B., Kegl, B., "The numerical simulation of biofuels spray", *Fuel*, **144** (pp. 71-79 (2015).
[14] Agarwal, A.K., Chaudhury, V.H., "Spray characteristics of biodiesel/blends in a high pressure constant volume spray chamber", *Experimental Thermal and Fluid Science*, **42** (pp. 212-218 (2012).
[15] Richards, K.J., Senecal, P.K., Pomraning, E., "CONVERGE (Version 2.1. 0) Theory Manual", *Convergent Science, Inc., Middleton, WI*, (2013).
[16] Ghahremani, A., Jafari, M., Ahari, M., Saidi, M., Hajinezhad, A., Mozafari, A., "Experimental and theoretical investigations on spray characteristics of bio-ethanol blends using a direct injection system", *SCIENTIA IRANICA*, **24** (1), pp. 237-248 (2017).
[17] Roisman, I.V., Araneo, L., Tropea, C., "Effect of ambient pressure on penetration of a diesel spray", *International journal of multiphase flow*, **33** (8), pp. 904-920 (2007).
[18] Ejim, C., Fleck, B., Amirfazli, A., "Analytical study for atomization of biodiesels and their blends in a typical injector: surface tension and viscosity effects", *Fuel*, **86** (10), pp. 1534-1544 (2007).
[19] Wu, Z., Zhu, Z., Huang, Z., "An experimental study on the spray structure of oxygenated fuel using laser-based visualization and particle image velocimetry", *Fuel*, **85** (10), pp. 1458-1464 (2006).
[20] Ghahremani, A., Ahari, M., Jafari, M., Saidi, M.H., Hajinezhad, A., Mozafari, A., "Experimental and theoretical study on spray behaviors of modified bio-ethanol fuel employing direct injection system", *Thermal Science*, **21** (1B), pp. 475-488 (2017).
[21] Ashgriz, N., Handbook of atomization and sprays: theory and applications, Springer Science & Business Media, 2011.