DOI: 10.52756/ijeim.2025.v01.i02.006 Int. J. Eng. Infor. Manag. 1(2): 63-74 (2025)

International Journal of Engineering and Information Management
Journal homepage: www.ijeim.in

Experimental Study of Spray Characteristics of Kerosene, Biofuels and Their Blends for Gas Turbine

Bodhisattwa Maity[*], **Sudipta Mondal**

Department of Mechanical Engineering, Shree Ramkrishna Institute of Science and Technology, Kolkata, 700150, India

***Corresponding Author:** bodhisattwa22jun@gmail.com

Article Information

Type of Article: Original
Received: Jan 21, 2025
Accepted: Mar 9, 2025
Published: Apr 15, 2025

Keywords:
Biofuel
Cone angle
Gas turbine
Methanol
Patternation
SVO

Cite this article:
Bodhisattwa Maity, & Sudipta Mondal. (2025). Experimental study of spray characteristics of kerosene, biofuels and their blends for gas turbine. *International Journal of Engineering and Information Management*, 1(2), 63-74.
DOI: 10.52756/ijeim.2025.v01.i02.006

Abstract

Conserving limited conventional fuel resources and searching for sustainable energy sources are becoming the necessities of the modern world. Methanol, SVO, biodiesel, kerosene methanol and kerosene biodiesel blends can be some suitable alternatives of kerosene, as a fuel. By using these fuels spray characteristics are done with a pressure swirl atomizer experimentally. This work also describes the preparation of biodiesel from straight vegetable oil (SVO) i.e. sunflower oil. Further sunflower oil biodiesel is blended in 5% and 10% by volume with kerosene. From the present study it has been found that, due to the low viscosity of methanol, the spray cone angle of the methanol blend is larger than kerosene. For the methanol blend more liquid mass is distributed in patternation whereas for kerosene less liquid mass is distributed mainly due to less cone angle. Further, it is seen that the cone angle of biodiesel blends is higher than that of kerosene for a certain flow rate due to the lower viscosity of biodiesel compared to kerosene. However, the cone angle of SVO is much less compared to other cases because of its high viscosity. The viscosity of sunflower oil is more than kerosene and the viscosity of biodiesel is less than kerosene. Therefore, with the increase in viscosity, FN increases from 10% blend, 5% blend, kerosene and then SVO. Thus, the power required for atomization of 10% blend is less than that for 5% blend of kerosene than that of SVO. For biodiesel blends more liquid mass is distributed in patternation whereas for kerosene less liquid mass is distributed mainly due to less cone angle. The above observation can conclude that we can adopt some of the biofuels fully or partially in a gas turbine engine with some modifications.

1 Introduction

Searching for reliable sustainable energy sources is the only solution to save both the environment and limited conventional energy reserves. The reserve of petroleum-fuels will be extinct in the very near future but despite the threat, the consumption predictions are increasing in coming years, thus modern industries have to immediately adopt some of the sustainable fuels. Last few years pollutant emissions from the combustion of hydrocarbons have been considered a major challenge to environmental sustainability (Lefebvre & Ballal, 2010). Fossil fuels are used in domestic, power and mostly by transportation sectors like gas turbine engines. Carbon emission is the ultimate cause of environmental pollution. Combustion of fossil fuel releases harmful carbon monoxide and carbon dioxide gasses which mix with air and then into water while raining causing both air and water pollution. However, biofuels like ethanol, methanol, straight vegetable oil (SVO), biodiesel etc. can be considered as an alternative source of energy. Furthermore, they will not cause pollution or carbon loading of the environment because of the carbon-neutral nature of these green fuels. Using sustainable and advanced hybrid energy sources efficiently and saving our green environment must be the first priority of modern industries.

Gas turbine combustor or in a liquid fuel furnace, the liquid fuel is sprayed at near-ambient pressure through atomizers (Panchasara et al., 2009). To achieve higher efficiency the liquid fuel is sprayed into finer particles with lesser droplet diameters and higher velocity in the combustion chamber with an optimum flame size. Atomizer and spray characteristics are of primary importance in the atomization of liquid fuel. Liquid dispersion, spray symmetry, the power required for atomization, and volumetric flux distribution all can be known from the atomizer and spray characteristics. These will be affected by some of the fuel properties like viscosity, surface tension, density, Reynolds number and Weber number etc. Methanol, SVO, biodiesel, kerosene methanol and kerosene biodiesel blends can be some suitable alternative of kerosene fuel as gas turbine engine fuel.

The operational performance of gas turbine engines heavily depends on the quality of fuel atomization and combustion process and these depend directly on the spray properties of fuel injection (Millo et al., 2013). The three main characteristics which affect fuel-air mixing and combustion stability while forming pollutants consist of droplet size distribution and spray angle and penetration. Research and industrial leaders show heightened interest in biofuels for gas turbines as environmental issues and fossil fuel scarcity increase (Welch & Igoe, 2015).

Biofuels from renewable biological raw materials show two major benefits through their ability to minimize greenhouse gases while enhancing sustainable operation. The implementation process of biofuels in gas turbine systems presents various difficulties. Biofuels demonstrate physical properties that deviate significantly from kerosene jet fuels such as viscosity density and surface tension which affect both spray behavior and combustion processes (Hassan & Khandelwal, 2014; Dafsari et al., 2018). The combination of kerosene with biofuels has become essential to achieve a balance between performance advantages and sustainability improvements, especially in military and commercial aviation requiring fuel reliability and adaptability (Kim et al., 2017).

The analysis of kerosene and biofuels and their mixed atomization patterns enables optimal turbine combustion efficiency together with safety guarantees and environmental consistency (Braun-Unkhoff et al., 2015). Research studies have found that modifications to fuel components cause major variations in spray behavior patterns and this affects combustion efficiency and emission pollution formation (Zhan et al., 2018; Serrano et al., 2015). High-pressure common rail systems from Payri et al. (2008) reveal that fuel delivery conditions especially pressure and temperature have substantial effects on the spray properties. Advanced diagnostic techniques composed of high-speed imaging phase Doppler anemometry and laser-induced fluorescence help researchers gain detailed information about droplet sizes, velocity distributions and spray morphology (Torres-Jiménez et al., 2010). The information gathered through experimental testing helps perfect computational fluid dynamics (CFD) models along with the development of upcoming combustor systems that support heterogeneous fuel selection. The experimental research examines the spray behavior of kerosene together with biofuel mixtures at parameters equivalent to gas turbine functioning conditions. This research evaluates important spray parameters which control atomization alongside spray development to understand fuel properties' effect on combustion patterns better. The research findings help advance efforts for developing gas turbines with improved fuel flexibility and both cleaner operations and higher efficiency.

The rest of the article proceeds as follows: Section 2 presents the background of the domain. Sections 3 and 4 explain the experiments and methodology of the study. In Section 5, results are presented and discussed. Finally, Section 6 concludes the study.

2 Background

Several researchers have analyzed the combination of biofuel blends together with kerosene as a potential power solution for gas turbines. The combustion efficiency in gas turbine combustors increases when fuel droplets get finer because enhanced evaporation helps improve performance according to Lefebvre (1985). The spray characteristics of kerosene were examined by Patra et al. (2019) through the use of a hollow cone atomizer which showed the resultant development of an air core within the operating conditions.

The researchers established that higher liquid flow rates made the cone angle expand yet the Sauter Mean Diameter (SMD) reduced between them indicating better atomization capabilities. The utilization of straight vegetable oil (SVO) alongside diesel-blended fuels in micro gas turbines was examined by Prussi et al. (2011) through their research which added to the scientific understanding of turbine systems using alternative fuels.

The researchers verified MGTs function effectively while utilizing straight vegetable oil SVO when using appropriate control parameters and minor adjustments to the system. Laboratory analysis showed that operating conditions alone did not affect carbon monoxide (CO) emissions recorded between SVO and conventional fossil fuel products. Zheng & Kong (2009) studied pure rapid pyrolysis bio-oil extracted from rice husk through internal mixing air-blast atomization and determined that bio-oil demonstrates suitable attributes to replace diesel fuel. The spray characteristics of sunflower SVO received analysis from Patra et al. (2019) through their utilization of hollow cones and twin-fluid atomizers. Pressure atomizers generated wider spray cones when flow rates and oil temperatures rose according to their experimental data. The spray cone angle of the twin-fluid atomiser maintained stability at different flow rates while it expanded with increasing oil temperature and air pressure. Basak et al. (2013) conducted research comparing twin-fluid and hollow cone pressure atomizers while working with sunflower SVO and its ester and they discovered that the lower viscosity of biodiesel caused both atomizer types to generate expanded spray cone angles than pure SVO. Few researches have examined the direct implementation of SVO in engine tests. Daho et al. (2012) verified MGTs function effectively while utilizing straight vegetable oil SVO when using appropriate control parameters and minor adjustments to the system. Laboratory analysis showed that operating conditions alone did not affect carbon monoxide emissions recorded between SVO and conventional fossil fuel products.

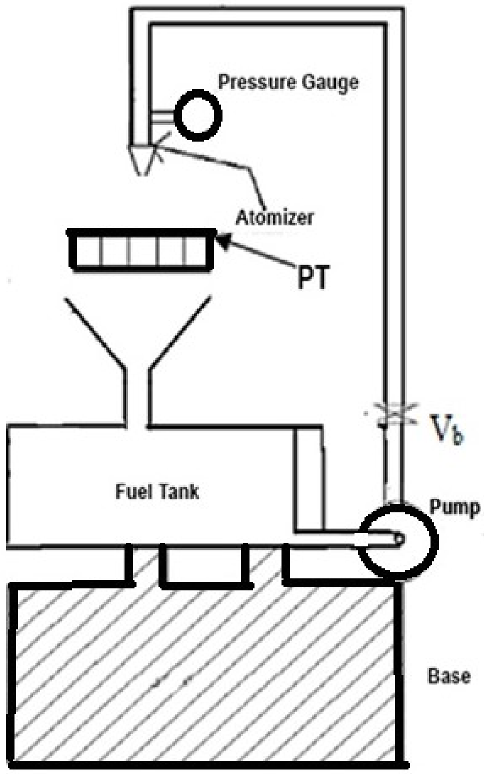
Specific fuel consumption increased while engine efficiency experienced a minor reduction because SVO possessed a lower heating value than other fuels. Atmospheric conditions enabled Deshmukh et al. (2012) to study SVO high-pressure spray characteristics which revealed that high viscosity caused longer injection delays than diesel and solid-liquid cores within the spray. Previous research has primarily studied SVO and biodiesel spray characteristics used in engine and furnace systems but the literature lacks information about comparing these fuels and their kerosene blends in gas turbine environments. This research examines the spray characteristics of spray cone angle and spray patternation together with the atomizer performance aspects of flow number and coefficient of discharge at ambient pressure using pressure swirl hollow cone atomizers. This paper evaluates the properties of kerosene as well as kerosene-methanol (5%) blends and SVO together with biodiesel and kerosene-biodiesel blends at 5% and 10% concentrations. The researchers compare these possible fuel alternatives for gas turbine use to decide their appropriateness while generating important findings for future sustainable combustion system development. The research results will yield advantages for scientists alongside energy solution initiatives focusing on cleanliness.

3 Experiments

The image and schematic of the experimental set up which is used to perform the experiments is shown in Figure 1 (a) and (b). The experimental setup has a gear pump which drives liquid fuel from a fuel tank through an atomizer and into the surrounding air. A needle valve (Vb) regulates the flow rate. Pressure differential in the nozzle is measured by the pressure transducer which is placed directly in front of it. A stopwatch and a graduated volume measuring flux are used to measure the flow rate. Cone angles of the sprays formed from the atomizers at various operating conditions have been measured from the captured images.

To measure the distribution of liquid mass flux within the spray, a mechanical patternator has been constructed. The patternator has small circular collection tubes of 15 mm diameter having thin walls. These collection tubes are placed in the radial direction from the centre of the spray. The tubes are placed in eight radial directions that are 450 mm apart from each other. Figure 2 exhibits the mechanical patternator used for the experiment.

(a) Before deformation by SHPB



(b) After deformation by SHPB

Figure 1: (a) Image and (b) schematic of the experimental setup.

Figure 2: Image of mechanical patternator used in the spray.

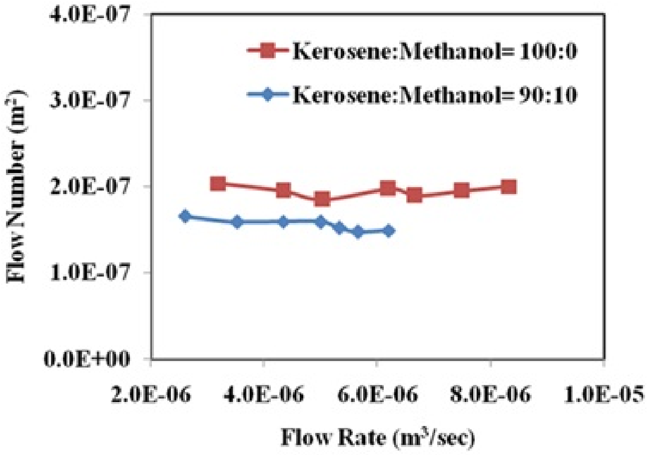


Figure 3: Shows the variation of flow number with flow rate for kerosene methanol blend using hollow cone atomizer.

4 Methodology

In this experiment, first, the specific atomizer performance and spray characteristics of the kerosene and kerosene-methanol blend are investigated. Then we used SVO, its biodiesel and kerosene-biodiesel blends for our experiment. The biodiesel is prepared by transesterification of sunflower oil. A hollow cone pressure swirl atomizer has been used in the experiment. In a pressure swirl hollow cone atomizer liquid is injected directly to the atomizer and the liquid comes out through a small orifice placed at the tip of the nozzle. Before starting experiments, it must be ensured that the nozzle tip plane is in a horizontal position. The diameter of the orifice of the pressure swirl hollow cone atomizer is 1.5 mm. The flow rate is measured by the volume collected in the volumetric flux for a certain time. The corresponding pressure drop reading is taken from the pressure transducer. The flow number (FN) is calculated using these measured values. The flow rate is varied and for each variation, the previous experiment has been done. For every flow rate, spray cone angles have been measured to determine the spray characteristics by taking images with a digital camera placed perpendicular to the spray. The cone angle of the spray is measured by drawing two straight lines tangent to the outermost periphery of the spray just coming out from the nozzle exit and measuring the included angle between the lines.

Patternation has been done at two several liquid pressures for a pressure swirl hollow cone. The patternator has been placed at 10 cm below the nozzle tip. Center point of the patternator must be just below the nozzle tip so that we get the spray pattern correctly. A calibrated syringe is used to draw the liquid of (5 ml) from the patternator block and the volume collected is measured. From this data liquid mass flux has been calculated. A contour plot has been plotted using these data. After each round of experimentation, the patternator must be thoroughly cleaned to avoid any residual error in the next experiment.

5 Results & Discussion

The variation of flow number with flow rate has been studied for pressure swirl hollow cone atomizer. As the flow number is dependent only on the atomizer dimension and liquid property, so for a certain atomizer with a specific liquid, the flow number is almost constant as in Figure 3. The viscosity of kerosene is higher than methanol. Therefore, with the increase in viscosity the pressure drop must be increased for a constant flow rate, reducing the flow number.

The flow number of different fuels is calculated by using Equation (1). In Figure 4 variation of flow number with flow rate has been studied for pressure swirl hollow cone atomizer. Viscosity of sunflower oil is more than kerosene and the viscosity of biodiesel is less then kerosene. Therefore, with the increase in viscosity, the FN increases for 5% blend, kerosene and SVO than 10% blend. The increment for kerosene and SVO is more because of the very high viscosity of SVO and also the same observation for kerosene and 5% because of drastic change in the viscosity by blending. Also, for hollow cone atomizer the power

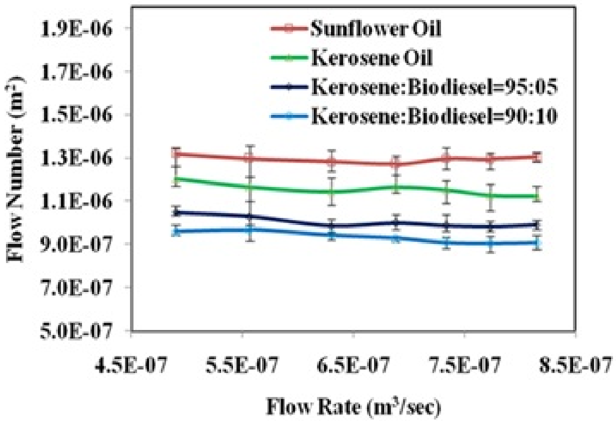


Figure 4: Shows the variation of flow number with flow rate for kerosene, SVO and kerosene biodiesel blend using hollow cone atomizer.

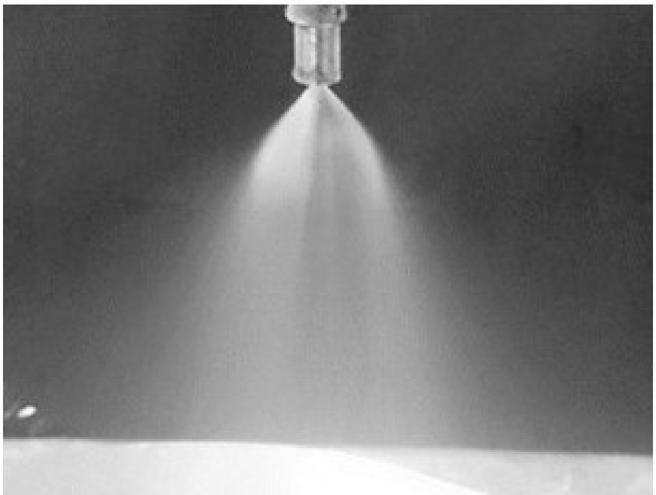


Figure 5: Images of kerosene spray using a hollow cone atomizer at 8 bar pressure.

required for atomization of 10% blend is less than that for 5% blend that of kerosene than that of SVO.

$$FN = \frac{\text{Flow rate, } kg/s}{(\text{Pressure Differential, Pa})^{0.5} \times (\text{Liquid Density, } kg/m^3)^{0.5}} \tag{1}$$

Figure 5 depicts the spray images issued from hollow cone atomizers taken by digital cameras. The respective spray cone angles have been determined from these images. Variation of spray cone angle with various flow rates has been studied and found that for pressure swirl hollow cone atomizer, cone angle enhances gradually with the flow rate (Figure 6). It has been also observed that for low flow rate for blends the increase in cone angle is small but with higher flow rate the increase is better. It is observed that for methanol blend the cone angle is more than kerosene for a certain flow rate due to less viscosity. It shows the presence of a fully developed air core in the spray and the cone angle increases with the increase in fuel flow rate. Due to the low viscosity of methanol, the spray cone angle of the methanol blend is larger than that of kerosene. Therefore, the blend mixes more rapidly with the surrounding gas. Spray angle exercises a strong influence in liquid combustion, pollutant emission by unburned hydrocarbons etc. Therefore, using blend-in combustors provides good combustion and less pollutant emission.

In Figure 7 it is observed that for a low flow rate for biodiesel kerosene blend the increase in cone angle is small but with a higher flow rate, the increase is better. It is also observed that for blends cone angle is more than kerosene for a certain flow rate due to less viscosity. The cone angle of SVO is very low compared to others because of high viscosity. Figure 8 (a) & (b) shows the spray patternation of kerosene and (c) & (d) for 10% methanol blend at two liquid pressures (2 bar and 4 bar) for hollow cone

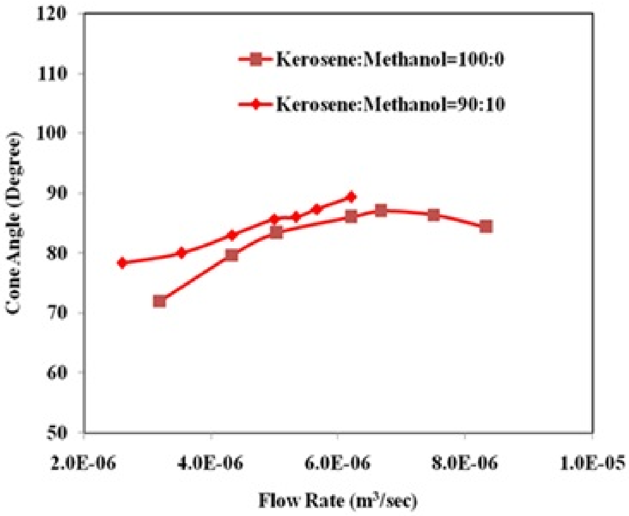


Figure 6: Variation of cone angle with flow rate for kerosene methanol blend using hollow cone atomizer.

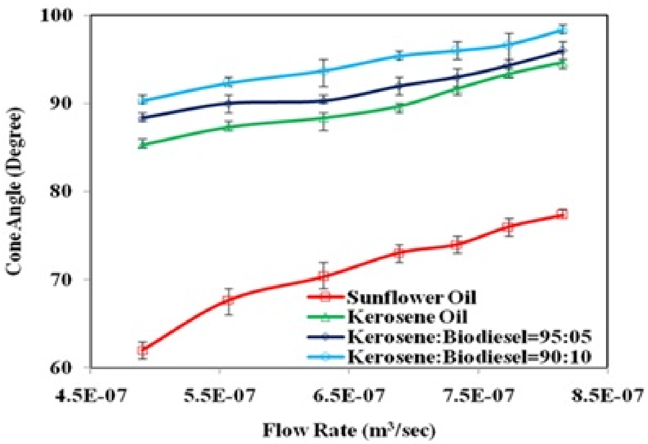


Figure 7: Variation of cone angle with flow rate for kerosene, SVO and kerosene biodiesel blends using hollow cone atomizer.

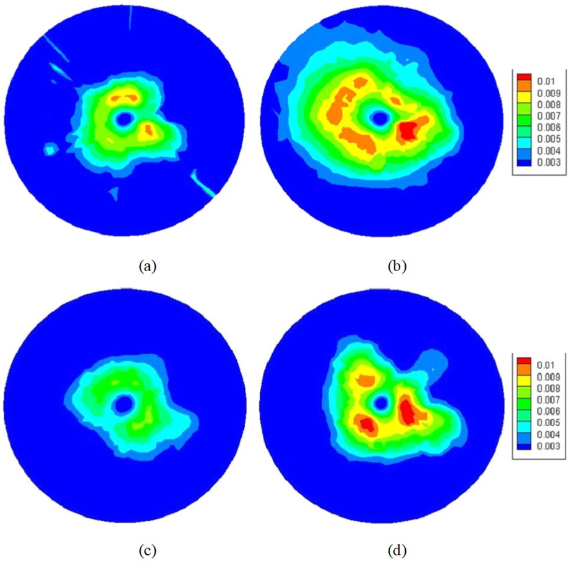


Figure 8: Patternation for (a) & (b) Kerosene and (c) & (d) Kerosene methanol blend with hollow cone atomizer at 2 bar and 4 bar pressures respectively.

atomizer respectively. The liquid distribution for the pressure swirl hollow cone atomizer shows that very little spray flux is present close to the axis. The maximum liquid mass flux is collected at a certain radial distance from the central axis. For 10% methanol blend the change in dispersion is less for both the pressures indicating a con angle change after blending. Figure 9 (a) & (b), (c) & (d), (e) & (f), (g) & (h) shows spray patternation of SVO, kerosene, 5% biodiesel and 10% biodiesel blend with kerosene at two liquid pressures (2 kg/cm^2 and 4 kg/cm^2) for respectively. Variation of pressure differential from 2 bar to 4 bar increases the dispersion pattern of the liquid. For the 10% blend, the change in dispersion is greater than the 5% blend, as well as for both pressures indicating a change in the angle of the cone after the blend. Similarly, the dispersion is higher for a 5% blend compared to kerosene at both pressures.

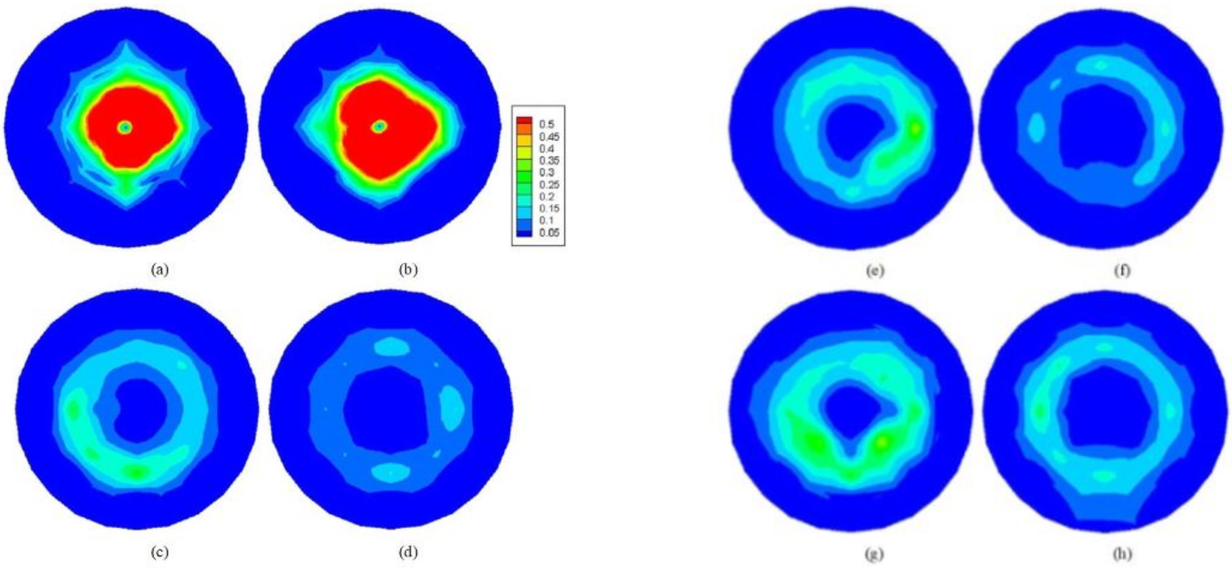


Figure 9: Patternation for (a) & (b) SVO, (c) & (d) kerosene, (e) & (f) 5% biodiesel blend and (g) & (h) 10% biodiesel blend with kerosene using hollow cone atomizer at 2 bar and 4 bar pressures, respectively.

The dispersion for SVO is very less compared to all other oils due to its viscous nature and lesser cone angle. The spray shows a higher dispersion at higher injection pressure or higher liquid flow rate. This corroborates the fact that spray cone angle depends on the liquid flow rate. It has been also observed for pressure swirl atomizers that the spray pattern becomes more symmetrical with an increase in the

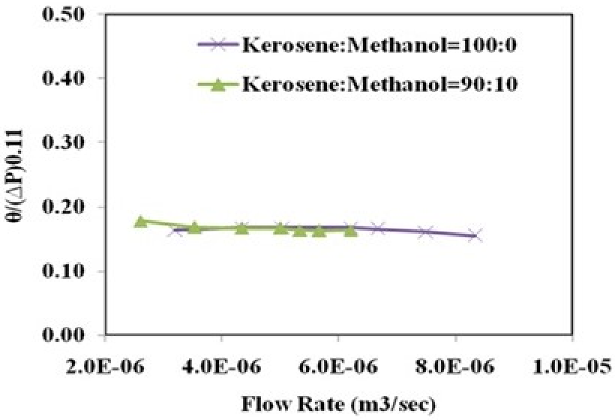


Figure 10: Shows the validation of Equation 1 and Equation 2 for various flow rate by using a hollow cone atomizer.

liquid pressure for hollow cone atomizers.

Rizk & Lefebvre (1985) used a theoretical approach to calculate the spray cone angle (2θ) in terms of liquid properties and applied pressure differential as given in Equation (2).

$$2\theta = 6K^{-0.15}(\frac{\Delta P d_0 l_l}{\mu_l^2})^{0.11} \tag{2}$$

According to the expression for a particular atomizer and for a particular liquid, $\frac{\theta}{\delta P^{0.11}}$ is constant. We have also plotted both the parameters for different flow rates of kerosene methanol blends. The plots corroborate the above condition as shown in Figure 10.

Giffen & Muraszew (1953) theoretically derived a relationship between the discharge coefficient, C_D and X, where X is the ratio of air core area to the area of the orifice for a hollow cone atomizer, as discussed in Basak et al. (2013). It was compared the calculated value of C_D, obtained theoretically with the direct experimental determination of C_D from liquid flow rate and pressure drop at different operating conditions. Figure 11 (a) and (b) shows the variation of direct experimental data of C_D is expressed as experimental work, while Giffen Muraszew Equations (1) and (2) show the variation of C_D obtained from Equation (3) and (4), respectively. It is seen from the figure that with the increase in flow rate, the experimental value is following the trend of Giffen Muraszew data but the value lies above them for both fuels, it may be due to the complex nozzle used in the experiment and due to the nozzle dimension. Figure 11 can be taken as a validation of the measurement technique employed in the test.

$$C_D = [\frac{(1-X)^3}{(1+X)}]^{0.5} \tag{3}$$

$$C_D = [\frac{(1-X)^3}{(1+X)}]^{0.5} \times 1.17 \tag{4}$$

In this experimental study, the flow number (FN) for various fuels was calculated and its variation with flow rate was analyzed for a pressure swirl hollow cone atomizer. It was found that fuels with higher viscosity, such as straight vegetable oil (SVO) and kerosene, exhibited a higher FN compared to lower-viscosity blends like the 10% biodiesel blend. This trend is consistent with the observation that an increase in fuel viscosity leads to an increase in FN. The increment was particularly noticeable for SVO and kerosene due to their significantly higher viscosities compared to blends.

The power required for atomization was also studied, revealing that the 10% blend required less power than the 5% blend, kerosene, and SVO, again due to its lower viscosity. Spray cone angle measurements showed that for the hollow cone atomizer, the cone angle increased with the flow rate. Blended fuels, especially methanol blends, demonstrated larger cone angles than pure kerosene, attributed to the reduced viscosity, which promotes better air core formation and improved atomization. SVO, being highly viscous, consistently showed the smallest cone angles. Spray patternation results indicated that liquid mass flux

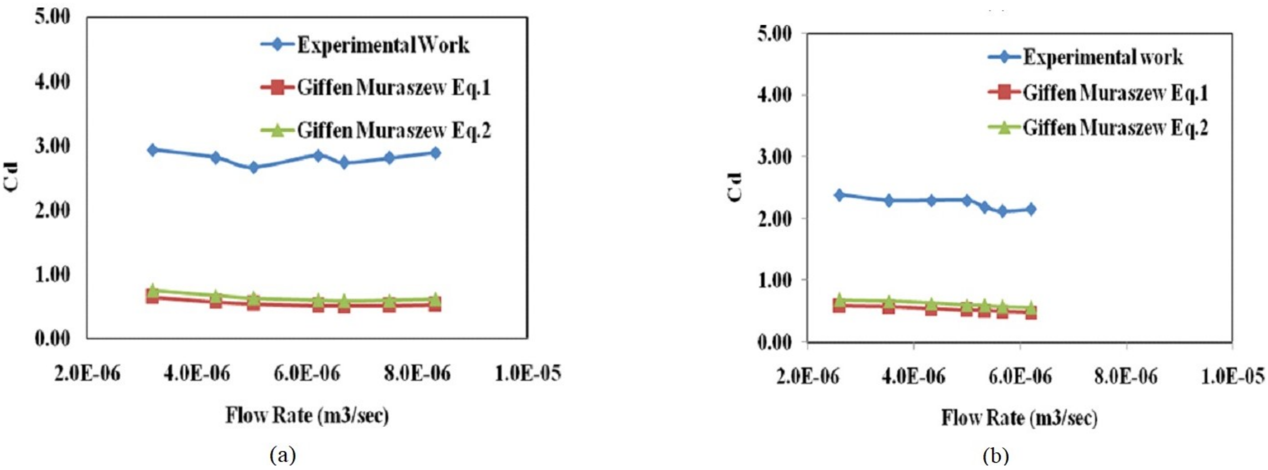


Figure 11: (a) Variation of CD with flow rate and comparison with eqn. 3 and eqn. 4 for kerosene and (b) for kerosene methanol blend at different flow rates.

peaked at a certain radial distance from the axis, with blends showing more dispersion than pure kerosene, and SVO showing the least dispersion. Higher injection pressures led to greater spray dispersion and more symmetrical spray patterns.

Finally, a comparison between experimentally determined discharge coefficients (CD) and theoretical values based on the Giffen-Muraszew relationship showed good agreement in trend, though the experimental values were slightly higher. This difference was attributed to the complexity of the experimental nozzle and dimensional factors, validating the experimental setup and measurement techniques used.

6 Conclusion

The research analyzed spray characteristic elements consisting of spray cone angle and spray patternation jointly with flow number and coefficient of discharge parameters at normal pressures through a pressure swirl hollow cone atomizer with kerosene and its subsequent blend combinations of kerosene-methanol (5%), straight vegetable oil (SVO), biodiesel and kerosene-biodiesel (5% and 10%). The atomizer-nozzle combination with any particular fluid produces intrinsic flow number and coefficient of discharge values when tested. Merging kerosene with lowering-viscosity methanol and biodiesel formations expanded spray cone dimensions which will increase fuel-air mixing and potentially achieve enhanced combustion efficiency combined with diminished pollutant formation of unburned hydrocarbons. The patternation results demonstrate that blends of biodiesel with methanol expand spray mass distribution because of their wider spray cone angles. The hollow cone atomizer produced better spray distribution when injection pressure increased combined with methanol mixtures while showing symmetric sprays patterns under high pressures. Biodiesel along with methanol blending improves atomization characteristics better than kerosene as fuel in gas turbine applications and makes them suitable for efficient and environmentally friendly combustion operations.

Conflict of Interest

The author declares that there is no conflict of interest in this work.

Data Availability

Data may be available on request.

References

Basak, A., Patra, J., Ganguly, R., & Datta, A. (2013). Effect of transesterification of vegetable oil on liquid flow number and spray cone angle for pressure and twin fluid atomizers. *Fuel*, *112*, 347–354. https://doi.org/10.1016/j.fuel.2013.05.047.

Braun-Unkhoff, M., Dembowski, J., Herzler, J., Karle, J., Naumann, C., & Riedel, U. (2015). Alternative fuels based on biomass: An experimental and modeling study of ethanol cofiring to natural gas. *Journal of Engineering for Gas Turbines and Power*, *137*(9). https://doi.org/10.1115/1.4029625.

Dafsari, R. A., Lee, H. J., Han, J., Park, D.-C., & Lee, J. (2018). Viscosity effect on the pressure swirl atomization of an alternative aviation fuel. *Fuel*, *240*, 179. https://doi.org/10.1016/j.fuel.2018.11.132.

Daho, T., Vaitilingom, G., Sanogo, O., Ouiminga, S., Segda, B., Valette, J., Higelin, P., & Koulidiati, J. (2012). Model for predicting evaporation characteristics of vegetable oils droplets based on their fatty acid composition. *International Journal of Heat and Mass Transfer*, *55*(11–12), 2864–2871. https://doi.org/10.1016/j.ijheatmasstransfer.2012.01.048.

Deshmukh, D., Mohan, A. M., Anand, T., & Ravikrishna, R. (2012). Spray characterization of straight vegetable oils at high injection pressures. *Fuel*, *97*, 879–883. https://doi.org/10.1016/j.fuel.2012.01.078.

Giffen, E. & Muraszew, A. (1953). *Atomization of Liquid Fuels*. Chapman and Hall. https://doi.org/10.1017/S0368393100097832.

Hassan, H. & Khandelwal, B. (2014). Reforming technologies to improve the performance of combustion systems. *Aerospace*, *1*(2), 67. https://doi.org/10.3390/aerospace1020067.

Kim, D.-H., Martz, J., Abdul-Nour, A., Yu, X., Jansons, M., & Violi, A. (2017). A six-component surrogate for emulating the physical and chemical characteristics of conventional and alternative jet fuels and their blends. *Combustion and Flame*, *179*, 86. https://doi.org/10.1016/j.combustflame.2017.01.025.

Lefebvre, A. H. (1985). Fuel effects on gas turbine combustion—ignition, stability, and combustion efficiency. *Journal of Engineering for Gas Turbines and Power*, *107*(1), 24–37. https://doi.org/10.1115/1.3239693.

Lefebvre, A. H. & Ballal, D. R. (2010). *Gas Turbine Combustion*. CRC Press. https://doi.org/10.1201/9781420086058.

Millo, F., Mallamo, F., Vlachos, T., Ciaravino, C., Postrioti, L., & Buitoni, G. (2013). Experimental investigation on the effects on performance and emissions of an automotive euro 5 diesel engine fuelled with b30 from rme and hvo. SAE Technical Papers on CD-ROM/SAE Technical Paper Series. https://doi.org/10.4271/2013-01-1679.

Panchasara, H. V., Simmons, B. M., Agrawal, A. K., Spear, S. K., & Daly, D. T. (2009). Combustion performance of biodiesel and diesel-vegetable oil blends in a simulated gas turbine burner. *Journal of Engineering for Gas Turbines and Power*, *131*(3). https://doi.org/10.1115/1.2982137.

Patra, J., Datta, A., Ganguly, R., Sen, S., Chatterjee, S., & Saha, R. (2019). Experimental investigations on spray and combustion characteristics of kerosene oil injected through pressure swirl atomizer. *Journal of the International Flame Research Foundation*, *13*, 2075–3071.

Payri, R., Salvador, F. J., Gimeno, J., & Bracho, G. (2008). Effect of fuel properties on diesel spray development in extreme cold conditions. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, *222*(9), 1743. https://doi.org/10.1243/09544070jauto844.

Prussi, M., Chiaramonti, D., Riccio, G., Martelli, F., & Pari, L. (2011). Straight vegetable oil use in micro-gas turbines: System adaptation and testing. *Applied Energy*, *89*(1), 287–295. https://doi.org/10.1016/j.apenergy.2011.07.031.

Rizk, N. K. & Lefebvre, A. H. (1985). Prediction of velocity coefficient and spray cone angle for simplex swirl atomizers. In *Proceedings of the 3rd International Conference on Liquid Atomization and Spray Systems* (pp. 111C/2/1–16). London.

Serrano, L., Lopes, M., Pires, N., Ribeiro, I., Cascão, P., Tarelho, L. A. C., Monteiro, A., Nielsen, O. J., Silva, M. G. d., & Borrego, C. (2015). Evaluation on effects of using low biodiesel blends in a euro 5 passenger vehicle equipped with a common-rail diesel engine. *Applied Energy*, *146*, 230. https://doi.org/10.1016/j.apenergy.2015.01.063.

Torres-Jiménez, E., Jerman, M. S., Gregorc, A., Lisec, I., Dorado, M. P., & Kegl, B. (2010). Physical and chemical properties of ethanol–diesel fuel blends. *Fuel*, *90*(2), 795. https://doi.org/10.1016/j.fuel.2010.09.045.

Welch, M. & Igoe, B. (2015). An introduction to combustion, fuels, emissions, fuel contamination and storage for industrial gas turbines. In *Turbo Expo: Power for Land, Sea, and Air*, volume *56680* (pp. V04AT04A002).: American Society of Mechanical Engineers. https://doi.org/10.1115/gt2015-42010.

Zhan, C., Feng, Z., Ma, W., Zhang, M., Tang, C., & Huang, Z. (2018). Experimental investigation on effect of ethanol and di-ethyl ether addition on the spray characteristics of diesel/biodiesel blends under high injection pressure. *Fuel*, *218*, 1. https://doi.org/10.1016/j.fuel.2017.12.038.

Zheng, J. & Kong, Y. (2009). Spray combustion properties of fast pyrolysis bio-oil produced from rice husk. *Energy Conversion and Management*, *51*(1), 182–188. https://doi.org/10.1016/j.enconman.2009.09.010.