Spray formation of biodiesel-water in air-assisted atomizer using Schlieren photography

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Abstract. Biodiesels are attractive renewable energy sources, particularly for industrial boiler and burner operators. However, biodiesels produce higher nitrogen oxide (NOx) emissions compared with diesel. Although water-emulsified fuels can lower NOx emissions by reducing flame temperature, its influence on atomization needs to be investigated further. This study investigates the effects of water on spray formation in air-assisted atomizers. The Schlieren method was used to capture the spray images in terms of tip penetration, spray angle, and spray area. The experiment used palm oil biodiesel at different blending ratios (B5, B10, and B15) and water contents (0 vol% – 15 vol%). Results show that water content in the fuel increases the spray penetration and area but reduces the spray angle because of the changes in fuel properties. Therefore, biodiesel-water application is applicable to burner systems.

1. Introduction

The introduction of the Clean Air Act Amendment in 1990 marked a change in the global environment as global warming effects became a worldwide concern. Biodiesel is an attractive alternative solution that helps reduce emissions from vehicles and stationary equipment. Studies show that nitrogen oxide (NOx) emissions increase owing to the physicochemical properties of biodiesel, including fuel viscosity and density [1-3]. To overcome this problem, the potential applications of water-emulsified fuels, especially in burner combustion technology, are studied.

Water-emulsified fuel is a potential solution that has been proven to reduce NOx and PM emissions [4-6]. It is capable of reducing fuel consumption due to its high combustion efficiency. Moreover, component modifications are not required when utilizing this system. The combustion of this emulsion is associated with micro-explosion, an unsteady burning process involving sudden droplet fragmentations.

Water-emulsified fuels have been receiving attention for their transport and non-transport applications. Most of the systems studied involve diesel fuel for CI engine applications [7]. The studies also focused on emulsified fuel, which uses surfactants in its composition. However, emulsification increases fuel viscosity, which subsequently affects combustion efficiency. Premixing fuel and water in the atomizer can overcome these problems and reduce the additional surfactant cost.
[8]. Therefore, the effects of premixing on the spray characteristics at different blending ratios and water contents need to be further investigated.

This study investigates the effects of biodiesel fuel on spray formation in air-assisted atomizers in burner systems. Three types of blended fuels, namely B5, B10, and B15, were used with 0 vol%–15 vol% premixed water. Schlieren photography was used to capture the images for analysis. The parameters studied in this investigation include spray length, spray angle, and spray area.

2. Methodology
The air-assisted atomizer is shown in Figure 1. The perforated plate is located inside the premixing chamber with 10 holes that are 2 mm diameter each. The plate functions as a turbulence generator to improve the mixing of fuel, water, and air inside the premixing chamber before spraying into the atmosphere [9]. The spray nozzle at the top of the chamber is 1 mm in diameter and has eight holes.

The atomizer was equipped with an air compressor to supply the primary air at the required pressure. The two pumps were used to supply fuel and water to the atomizer. A flow meter was used to control the water flow rate, and the fuel was controlled by the Ono Sokki mass flow meter. The schematic diagram of the experiment is in Figure 2. The equipment and experimental condition are shown in Table 1. The investigation was conducted at five equivalence ratios from 0.6 to 1.4. The fuel and water flow rates are shown in Table 2, and the blended fuel properties are shown in Table 3.

Schlieren photography was set up according to Figure 3. Parallel light from the LED lamp was focused on the first concave mirror, transmitted through the test region, and reflected to a focal point where the knife edge was located [10-11]. Flat reflecting mirrors were used to save space. Finally, the video was recorded using a digital single-lens reflex (DSLR) camera for 20 seconds and processed for analysis.

Spray images were initially recorded using the DSLR camera. The video was taken with a duration time of 20 seconds from the initial fuel and air supply until the maximum penetration. The video was then converted to real images using GomPlayer software. The spray images are shown in Figure 3. Solidwork was used to measure the length penetration, angle, and area of the spray. The measurements were also compared with an actual 10 cm-high bar in the experiment. The eight spray jets visually produced more consistent and homogeneous sprays as the equivalence ratio increased, compounded by the improved atomization for the two-phase atomizer because of the increase in fuel flow rate [12-13].
Figure 2. Experimental setup

Table 1. Equipment and experimental specifications

| Equipment            | Model               | Specification          |
|----------------------|---------------------|------------------------|
| **Air Compressor**   | QUASA HDC-D3050     |                        |
|                      | Capacity, L/min     | 200                    |
|                      | Pressure, kg/cm²    | 8                      |
| **Water Pump**       | SFDP1-014-080-22-Seaflo |                        |
|                      | Voltage, V          | 12                     |
|                      | Flow rate, L/min    | 5.1                    |
| **Fuel Pump**        | CNY-3805            |                        |
|                      | Pressure, bar       | 3                      |
|                      | Flow rate, L/hr     | 100                    |
| **DC Voltage Regulator** | Teletron TC-1206A |                        |
|                      | Current, A          | 64 (max)               |
| **Operating condition** | Air Pressure, MPa  | 0.1                    |
|                      | Air Density, kg/m³  | 1.16                   |
|                      | Ambient Temperature, K | 300              |
|                      | Equivalence Ratio   | 0.6 - 1.4              |
Table 2. Equivalence ratio and mass flow rate of fuel and water

| Equivalence ratio, \( \phi \) | Fuel mass flow rate (kg/hr) | W0 (cc/min) | W5 (cc/min) | W10 (cc/min) | W15 (cc/min) |
|-------------------------------|----------------------------|-------------|-------------|--------------|--------------|
| 0.6                           | 4.244                      | 0           | 4.915       | 9.829        | 14.74        |
| 0.8                           | 5.658                      | 0           | 6.552       | 13.10        | 19.65        |
| 1.0                           | 7.074                      | 0           | 8.191       | 16.38        | 24.57        |
| 1.2                           | 8.488                      | 0           | 9.829       | 19.65        | 29.48        |
| 1.4                           | 9.905                      | 0           | 11.47       | 22.94        | 34.41        |

Table 3. Blended fuel properties

| Fuel Type | Properties         |
|-----------|--------------------|
|           | Density (g/cm³)    | Viscosity (mm²/s) | Flashpoint (°C) |
| STD       | 0.8368             | 2.7109            | 80.0            |
| B5        | 0.8440             | 3.4615            | 91.5            |
| B10       | 0.8456             | 3.4985            | 92.0            |
| B15       | 0.8486             | 3.5755            | 93.5            |

Figure 3. Schematic diagram of Schlieren-Z setup showing the image captured from an open area

3. Results and discussion

Figures 4(a) and (b) show the spray penetration, spray angle, and spray area at different equivalence ratios for diesel fuel and biodiesel (B5, B10, and B15) in 0vol% and 5vol% water content mixtures. At 0vol% water content, B15 showed the highest values of spray length, angle, and area, followed by B10; whereas B5 and diesel had similar characteristics. Different viscosity and density values were the main factors for these results.

Figure 4(b) depicts the spray characteristics of 5vol% water content. The water had increased spray length and angle, whereas the spray area of B15 was reduced. However, B15 spray penetration remained the highest among the fuels.
In Figure 5, B15 spray penetration produced the highest elongation within the equivalence ratio from 0.6 to 1.4; however, B10 still showed the highest spray area. This trend changed in Figure 5(b) at 15vol% water content, wherein B15 had the highest spray penetration and area. Overall, from 0vol% to 15vol% water content, B10 and B15 showed significant changes in spray penetration and area, whereas increases in density and viscosity of the higher ratio of blended fuels (B10 and B15) increased the penetration and area of spray.

Water addition is crucial in this experiment. The premixing water enhanced the penetration length and spray area. Increased water content into the fuel increased the spray penetration and area because of the influence of viscosity and density during the premixing of fuel, water, and air inside the chamber. However, viscosity in the presence of water was not determined in this study. Furthermore, spray angle decreased as water injection increased. The W0 showed the highest spray angle, whereas W15 had the lowest, a result that indicated spray angle is inversely proportional to the water content.

Spray area was likewise influenced by spray penetration; that is, the higher the spray penetration, the wider the spray area. The W15 produced the widest area owing to its penetration length being the highest, although its spray angle was smaller compared with those of other water contents. This result is attributed to the effect of water content on fuel viscosity, which influences the spray formation of the blended fuel.

**Figure 4.** Comparison of graph at (a) W0 and (b) W5
4. Conclusion
The results can be concluded as follows:

i. Blended fuels from B5 to B15 produce longer spray penetration and wider spray area compared with those of diesel. Moreover, the fuel with higher water content can produce a longer spray penetration and a larger spray area but a smaller spray angle. This outcome is due atomization quality and penetration being affected by the changes in fuel viscosity and density. Premixing of water before spraying also contributes to the macroscopic behavior of the spray formation.

ii. The presence of water in the burner combustion can significantly reduce nitrogen oxide (NOx), carbon monoxide, and hydrocarbon, because adding water to the spray combustion can reduce local flame temperature, the main contributor to NOx formation. Therefore, this work can help improve combustion efficiency and align the emission regulations for industrial burners.

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References

[1] Palash SM, Kalam MA, Masjuki HH, Masum BM, Fattah IR and Mofijur M 2013 Impacts of biodiesel combustion on NOx emissions and their reduction approaches Renewable and Sustainable Energy Reviews 23:473-90
[2] Ocampo-Barrera R, Villasenor R and Diego-Marin A 2001 An experimental study of the effect of water content on combustion of heavy fuel oil/water emulsion droplets Combustion and Flame 126(4):1845-55
[3] Chin, R.Y.S., Khalid, A., Ghan, A.M.A., Issak, M.M., Amirnordin, S.H., “A comparison between the fractal and swirl injector of diesel spray characteristics in the burner system”, ARPN Journal of Engineering and Applied Sciences, Volume 11, Issue 12, 1 June 2016, Pages 7491-7497.
[4] Khalid, A., “Effect of Ambient Temperature and Oxygen Concentration on Ignition and Combustion Process of Diesel Spray”, Asian Journal of Scientific Research, Volume 6, Issue 3, 2013, Pages 434-444, Asian Network for Scientific Information, DOI: 10.3923/ajsr.2013.434-444
[5] Fuchihata M, Takeda S and Ida T 2006 Observation of microexplosion in light oil-water emulsion spray flame 2nd Report, Influence of Temporal and Spatial Resolution in High Speed Videography
[6] Yatsufusa T, Kumura T, Nakagawa Y and Kidoguchi Y 2009 Advantage of using water-emulsified fuel on combustion and emission characteristics Fuel 5(60)
[7] Lif A and Holmberg K 2006 Water-in-diesel emulsions and related systems Advances in colloid and interface science 123:231-9
[8] Yatsufusa T, Kidoguchi Y and Nakagawa D 2014 Improvement of emissions and burning limits in burner combustion using an injector on the concept of fuel-water internally rapid mixing Journal of Energy and Power Engineering 8(1) 11-9
[9] Othman MF, Manshoor B and Khalid A 2013 Circle grid fractal plate as a turbulent generator for premixed flame: an overview In IOP Conference Series: Materials Science and Engineering (Vol. 50, No. 1, p. 012050) IOP Publishing
[10] Wang Y and Zhang Y 2015 Simultaneous high speed Schlieren and direct imaging of ignition process with digitally enhanced visualisation Energy Procedia 66:241-4.
[11] Hargather MJ and Settles GS 2012 A comparison of three quantitative Schlieren techniques Optics and Lasers in Engineering 50(1):8-17.
[12] Khalid, A., Tamaldin, N., Jaat, M., Ali, M.F.M., Manshoor, B., Zaman, I., “Impacts of Biodiesel Storage Duration on Fuel Properties and Emissions”, Procedia Engineering, Volume 68, 2013, Pages 225-230, Elsevier Ltd, DOI: 10.1016/j.proeng.2013.12.172
[13] Khalid, A., Amirnordin, S.H., Lambozi, L., Manshoor, B., Sies, M.F., Salleh, H., “Spray Characteristic of Diesel-Water Injector for Burner System”, Advanced Materials Research, Volume 845, 2014, Pages 66-70, Switzerland, DOI: 10.4028/www.scientific.net/AMR.845.66.