International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 281

DIRECT NUMERICAL SIMULATION OF THE NEAR FIELD CHARACTERISTICS OF POWER-LAW BIOFUEL SPRAYS

Daokuan Jiao, Kui Jiao, Qing Du*
State Key Laboratory of Engines, Tianjin University, 135Yaguan Rd, Tianjin, China, 300350
*Corresponding author emails: duqing@tju.edu.cn.

ABSTRACT

The spray characteristics of a fuel injection is highly dependent on the fluid transport properties. Different from gasoline and diesel, some biofuels behave as a non-Newtonian fluid whose viscous properties are a function of shear rate. The spray performance of these fuels still remains unclear, which will further impact the air-fuel mixture and combustion properties. In this paper, direct numerical simulation (DNS) coupled volume of fluids (VOF) method is adopted to investigate the near field spray characteristics of cylinder power-law fuel jets. Liquid jet evolution process which transforms from liquid column to droplet parcels has been detected. The evolution differences which include liquid column shapes, penetration lengths and surface wavelengths have been considered. The breakup differences of the liquid column deformation degrees, ligament types and droplet sizes have been analyzed. Compared to Newtonian and shear-thickening fluids, shear-thinning fuels have a better atomization effect with a smaller droplet size and a larger penetration length.

Keywords: Biofuel spray, DNS, Power-law index, Liquid-gas density and viscosity ratios

1. INTRODUCTION

Due to the non-renewable consumption of the fossil fuel resource, there is an ever-increasing attention on the research of alternative fuels. Biofuel, such as biodiesel, has been introduced in more and more practical applications [1]. Act as a kind of sustainable energy approaches, biofuel can be produced from many common crops as corn and palm. Of course, biofuel can also be taken from algae which has attracted dramatic attention so far due to its strong converting potential.

According to some research results [2], part of biofuels cannot be regarded as traditional Newtonian fluid. Instead, they must be thought as non-Newtonian fluids which means that their viscous properties are a function of shear rate rather than a constant. This difference indicates that the atomization properties and the combustion process of biofuel may be not the same as those of diesel and gasoline.

Experimental method is a comparatively popular tool in studying fuels injection. Mo et al. [3] employed a high-pressure common rail injection system to investigate the spray and atomization characterizes of n-butanol and soybean biodiesel blends. Due to the higher viscosity and surface tension, longer tip penetration and larger droplet diameters were observed for the soybean biodiesel compared to the blends which contained 20% n-butanol. What's more, the spray area also presented the same trend. Li et al. [4] studied the spray characteristics of biodiesel-pentanol blends under various working conditions using the high-speed photography technology. The experiments were conducted on a common-rail system and in a constant volume chamber. Also, the spray tip penetration, tip speed and spray cone angle were compared and analyzed. Besides, compared to biodiesel and diesel, it seems that the blended fuels spray structures were more likely to fluctuate. Guan et al. [5] investigated the atomization characteristics of soybean biodiesel, di-n-butyl ether (DBE)/ biodiesel blends and 0# diesel at different injection conditions. They found that the addition of DBE could bring about smaller SMD which means a better atomization. Compared to conventional diesel, the DBE addition was significantly effective in increasing the biodiesel atomization qualities.

From the literature view, the fluid properties, namely, viscosities and surface tension force, are thought to be the key factors on the atomization process of biodiesel. With optical test technology, diversiform injection settings and various nozzle types have been carried out. However, the studies of the biodiesel rheological properties are rather few. Moreover, the incident light ray of the conventional optical techniques is sensitive in the multiple scattering process, so it is not able to fully penetrate the high dense liquid jet column and droplets clusters. Therefore, many breakup details or evolution process, especially in the near nozzle fields, cannot be captured precisely.

So, in this work, considering the turbulent effect as the injection perturbation, DNS coupled VOF method is adopted to investigate the near field characteristics of power-law biofuel sprays under various conditions.

2. NUMERICAL METHODS

2.1 Governing equations

Since the evolution and atomization of fuel injection from the nozzles is a complicated two-phase flow problem, it's critical to capture the liquid-gas interface precisely. Here, two immiscible fluids flow formulation coupled with a modified VOF method is adopted to solve the liquid injection problems. An incompressible, isothermal condition is made for the present model. The governing equations are given below.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \quad (1)$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot (\rho \vec{U}\vec{U}) - \nabla \cdot \vec{\tau} - (\nabla \vec{U}) \cdot \nabla \alpha = -\nabla p_d - \vec{g} \cdot \vec{x} \nabla \rho + C\kappa \nabla \alpha \quad (2)$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot \alpha \vec{U} + \nabla \cdot [\vec{U}_\alpha \alpha (1-\alpha)] = 0 \quad (3)$$

$$\rho = \alpha_1 \rho_l + (1-\alpha_1)\rho_g, \quad \mu = \mu_l \alpha + \mu_g (1-\alpha) \quad (4)$$

$$\vec{U}_\alpha = \vec{U}_l - \vec{U}_g \quad (5)$$

The continuous, momentum and phase fraction equations are Eqs. (1-3), where C, μ, α, κ are the surface tension coefficient, dynamic viscosity, phase fraction and mean curvature of the free surface respectively. It can be noticed that in the momentum equation, $\tau = -\nabla \cdot \eta (\nabla \vec{U} + (\nabla \vec{U})^t) = -\eta \dot{\gamma}$ is the stress tensor, where superscript "t" represents transpose. According to the previous studies, the power-law fluids would be defined as $\eta = k\gamma^{n-1}$, where k is the fluid consistency number and n represents the power-law index number. When n < 1, it behaves as shear-thinning fluid while n > 1 the shear-thickening fluid, and Newtonian fluids correspond to n = 1.

2.2 Computational domain

In order to investigate the near field characteristics of the power-law fuel spray, a cylindrical computational domain is adopted, in which a round injection orifice is set in the center of the left surface, presented in Fig .1. The nozzle diameter D is consistent with the previous work, D = 2mm [6]. The computational domain length and width are 20D and 10D, respectively.

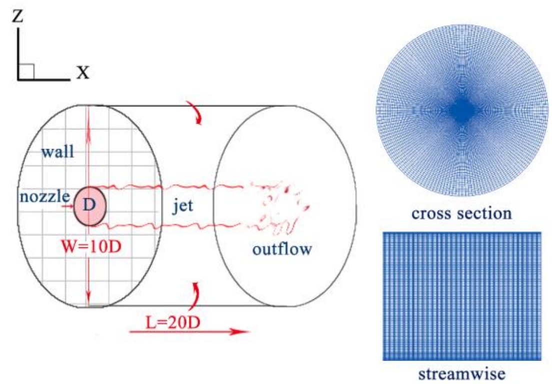

Fig 1 The computational domain and the meshes in cross-section and streamwise direction

The average injection velocity is 10m/s. The initial inlet velocity distribution satisfies a fully developed turbulent flow velocity distribution which varies parabolically through the nozzle radius. After that, the turbulence effect on fuel atomization is investigated by superposing certain turbulent intensities on the parabolic flow field. The turbulent integral length scale is fixed to be a quarter of nozzle diameter. Here, 600 uniform grids are distributed in flow direction resulting the resolution of 66μm, and almost 14.5 million hexahedron grids are adopted for the whole domain, which basically satisfy the Kolmogorov scale.

To maintain the numerical stability, the Courant number ($Co = (\delta t |U|) / \delta x \le 0.3$) is limited to less than 0.3, where δt is the time step , |U| the velocity magnitude flow through the grid and δx the grid size. Present study is carried out in an open-source software package OpenFOAM. The two-phase solver "interFoam" developed in the OpenFOAM platform are chosen. In the governing equations, the gradient, laplacian, divergence and time terms are discretized with a second order numerical precision.

3. RESULTS AND DISCUSSION

In our previous study [7, 8], the robust of the solver to predict the fuel spray evolution process has been tested. Accounting for turbulent perturbation as the main contributor to fuel injection breakup, the near nozzle field characteristics of the liquid column deformation and breakup under turbulent field have been compared to experimental and numerical result.

Therefore, it is reliable to study the power-law fuel sprays using the current method.

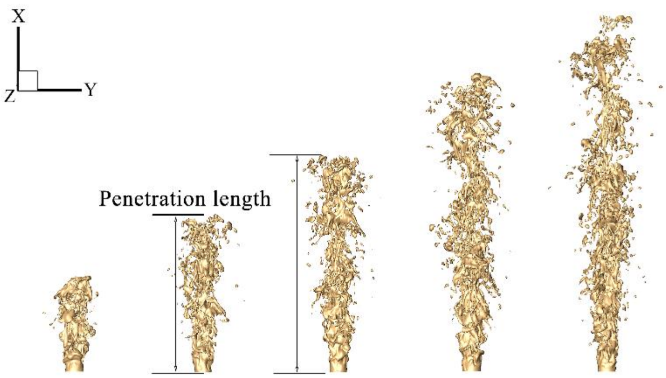

Fig 2. Liquid jet evolution process.

One of the spray evolution process is given in Fig. 2, at 1 ms, 2 ms, 3 ms, 4 ms and 5ms. in which the turbulence intensity is 15% and the power-law index *n* = 0.4, liquid-gas density ratio ρ_l / ρ_g = 20, viscosity ratio μ_l / μ_g =110. The liquid phase fraction iso-surface value is 0.5. With the development of spray evolution, the liquid main column becomes thinner, meanwhile the atomization quality is better. In the later stage of the liquid injection, the liquid column even breaks into ligaments with diversiform shapes and droplet parcels with various sizes. The temporal penetration length is defined as the distance from nozzle exit to liquid jet tip displayed in Fig. 2. The penetration length trend is showed to be mainly influenced by the liquid column velocity and the atomization effect.

Higher backpressure results in more flow resistance and reducing the penetration length. In addition, better atomization means a smaller liquid phase fraction, presented in Fig. 3.

Fig. 4 describes how a fuel injection breaks up from a liquid column to ligaments or droplet parcels with various shapes. In view of the stationary ambient, when the jet starts, the tip region forms easily to a mushroom shape and then break up in the first place. Therefore, the tip region breakup process of the liquid column is not considered. It can be clearly detected that the liquid column fluctuates under the turbulent condition to be wavy in the initial stage. The highly unstable wavy surface keeps growing in the subsequent stage which results in a severe deformation of the liquid column.

Under the expansion and surrounding gas shearing, the liquid column starts to disintegrate to tongue-shaped ligaments. This ligament is perforated in the middle and further breaks up into spindly ligaments with different sizes and shapes. Sometimes however, some severe deformation ligaments will separate from the liquid column directly. These ligaments will then shrink to large sizes droplets under the surface tension force. Moreover, in spite of the secondary breakup, small droplets can break up from the separated ligaments before and during the shrinking process as well. However, in an intensively breakup injection process, the four stages will be blurry.

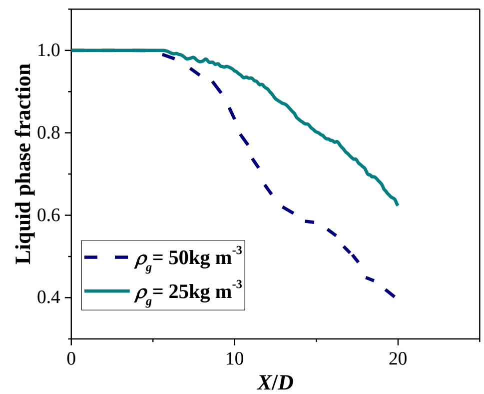

Fig. 3. The central lines extracted from the temporal average liquid phase fractions to show the backpressure effect

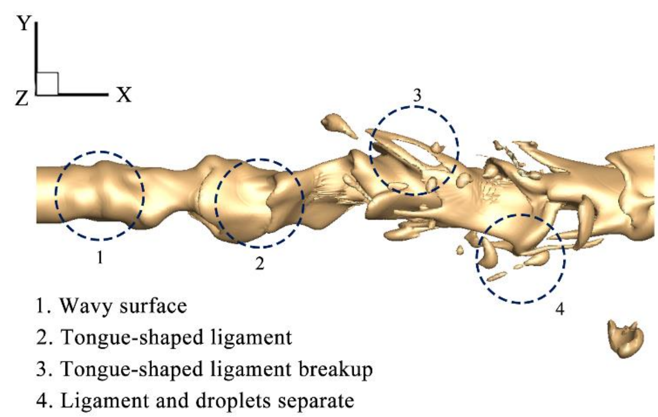

Fig 4. The four typical stages during a liquid spray breakup process.

The effect of the power-law index number on the fuel injection process is given in Fig. 5. As mentioned, the viscosities of the power-law fuels vary dramatically, but behave as shear-thinning properties. In order to reflect the effect of the power-law index number, the shear-thickening fluids are also taken into consideration in the beginning. The results of three different power-law index are compared. It is shown that both the shear-thinning (*n* = 0.6) and Newtonian fuel (*n* = 1) have a good atomization effect under the current circumstance compared to the shear-thickening fluid (*n* = 1.4).

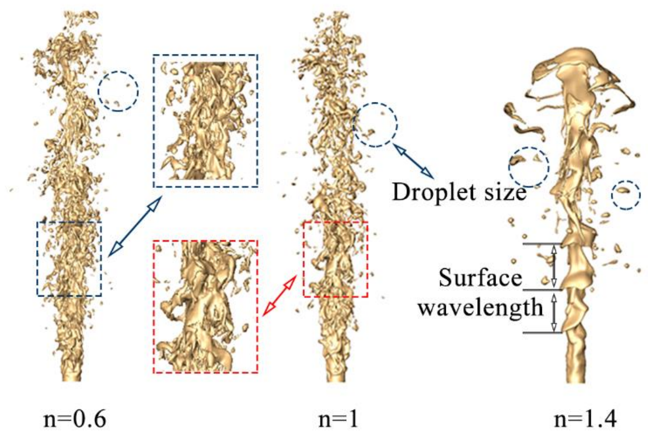

Fig 5. The effect of the power-law index number on the fuel injection process

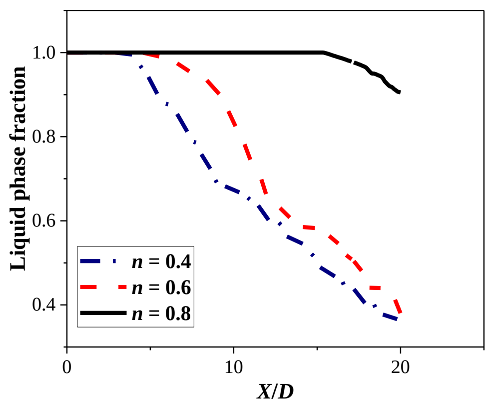

Fig. 6. The central lines extracted from the temporal average liquid phase fractions to show the power-law index effect

However, the further comparison is made in the enlarged dashed boxes of the shear-thinning and Newtonian cases in Fig. 5. In terms of the liquid column breakup, the shear-thinning fuel breaks up more intensively and thoroughly. Much more ligaments and droplets are observed, meanwhile, the liquid column is much thinner in the later stage. What's more, the shear-thinning fuel atomization takes the smallest droplet size distribution and the shortest surface wavelength while the shear-thickening fluid shows the opposite trend, implying the shear-thinning behavior can lead to a better atomization effect under the same condition. Further, the comparison of three different shear-thinning fuels reveals are given in Fig. 6. In this way, the shear-thinning biodiesels would be characterized by less injection requirements as compared with the traditional ones. Therefore, it is more reasonable to develop a power-law injection model to investigate the spray characteristics of biofuels.

4. CONCLUSIONS

The near nozzle field spray characteristics of the power-law behavior and Newtonian biofuels have been investigated by a 3-D DNS coupled VOF method. The results prove that the power-law behavior rheology should be taken into consideration of numerical models in fuel sprays. Generally, the droplet size for power-law behavior biofuels is smaller and achieves a better atomization. A lower power-law index leads to better atomization, what's more, the droplet size also presents an increase tendency with the increase of power-law index number. A higher gas density and inlet perturbation will accelerate the breakup process under the same conditions.

ACKNOWLEDGEMENT

Present study is supported by the National Natural Science Foundation of China (Grant No. 51676135).

REFERENCE

[1] Rajak U, Nashine P, Verma T N. Assessment of diesel engine performance using spirulina microalgae biodiesel[J]. Energy, 2018.

[2] Wileman A, Ozkan A, Berberoglu H. Rheological properties of algae slurries for minimizing harvesting energy requirements in biofuel production[J]. Bioresource technology, 2012, 104: 432-439.

[3] Mo J, Tang C, Li J, et al. Experimental investigation on the effect of n-butanol blending on spray characteristics of soybean biodiesel in a common-rail fuel injection system[J]. Fuel, 2016, 182: 391-401.

[4] Li F, Fu W, Yi B, et al. Comparison of macroscopic spray characteristics between biodiesel-pentanol blends and diesel[J]. Experimental Thermal and Fluid Science, 2018, 98: 523-533.

[5] Guan L, Tang C, Yang K, et al. Effect of di-n-butyl ether blending with soybean-biodiesel on spray and atomization characteristics in a common-rail fuel injection system[J]. Fuel, 2015, 140: 116-125.

[6] Bai F, Chang Q, Chen S, et al. Experimental investigation on the spray characteristics of power-law fluid in a swirl injector[J]. Fluid Dynamics Research, 2017, 49(3): 035508

[7] Jiao D, Zhang F, Du Q, et al. Direct numerical simulation of near nozzle diesel jet evolution with full temporal-spatial turbulence inlet profile[J]. Fuel, 2017, 207: 22-32.

[8] Jiao D, Jiao K, Zhang F, et al. Direct numerical simulation of droplet deformation in turbulent flows with different velocity profiles[J]. Fuel, 2019, 247: 302-314.