Hindawi Publishing Corporation
International Journal of Chemical Engineering
Volume 2014, Article ID 702890, 13 pages
http://dx.doi.org/10.1155/2014/702890

Research Article

A Numerical Study of Spray Characteristics in Medium Speed Engine Fueled by Different HFO/n-Butanol Blends

Hashem Nowruzi, Parviz Ghadimi, and Mehdi Yousefifard

Department of Marine Technology, Amirkabir University of Technology, Hafez Avenue, No. 424, P.O. Box 15875-4413, Tehran, Iran

Correspondence should be addressed to Parviz Ghadimi; pghadimi@aut.ac.ir

Received 25 January 2014; Accepted 13 March 2014; Published 22 May 2014

Academic Editor: Evangelos Tsotsas

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In the present study, nonreacting and nonevaporating spray characteristics of heavy fuel oil (HFO)/n-butanol blends are numerically investigated under two different high pressure injections in medium speed engines. An Eulerian-Lagrangian multiphase scheme is used to simulate blend of $C_{14}H_{30}$ as HFO and 0%, 10%, 15%, and 20% by volume of n-butanol. OpenFOAM CFD toolbox is modified and implemented to study the effect of different blends of HFO/n-butanol on the spray characteristics at 600 and 1000 bar. To validate the presented simulations, current numerical results are compared against existing experimental data and good compliance is achieved. Based on the numerical findings, addition of n-butanol to HFO increases the particles volume in parcels at 600 bar. It was also found that blend fuels increase the number of spray particles and the average velocity of spray compared to pure HFO. Moreover, under injection pressure of 1000 bar, HFO/n-butanol blends compared to pure HFO fuel decrease particles volume in parcels of spray. Another influence of HFO/n-butanol blends is the decrease in average of particles diameter in parcels. Meanwhile, the effect of HFO/n-butanol on spray length is proved to be negligible. Finally, it can be concluded that higher injection pressure improves the spray efficiency.

1. Introduction

Main fuel for medium and low speed engines such as large marine diesel engines, due to its cheaper price, is heavy fuel oil. These fuels have low quality and high emissions. As a result, fuel additives play an important role in reduction of pollution in medium and low speed diesel engines. One solution to enhance the quality of heavy fuel and decrease its emissions is addition of alcohols such as ethanol, methanol, and butanol to the reference fuel. Research indicates a higher comparative advantage of butanol relative to ethanol and methanol in combination with diesel fuels [1].

A number of studies related to butanol-diesel that were published between 1989 and 2013 in Scopus database can be seen in Figure 1. This figure clearly reflects the growing interests of this issue in recent years.

There have been several studies dealing with the blend of butanol with diesel fuels, thus far.

Rakopoulos et al. [2] studied heavy-duty direct injection diesel engine combustion and emission operating on ethanol or n-butanol diesel fuel blend. In their work, 5% and 10% of ethanol were blended with diesel fuel which led to a decrease in smoke density. Also, 8% and 16% of n-butanol blended with diesel fuel resulted in more decrease of NO_x emission and brake specific fuel consumption than ethanol. Miers et al. [3] experimentally investigated the effect of 20% and 40% by volume blending of butanol with ultra-low-sulfur diesel fuel on performance and emission of a Mercedes-Benz C220 turbo diesel vehicle. Their research demonstrates that by enhancing the volume fraction of butanol, fuel consumption is increased and NO_x emission is decreased. Rakopoulos et al. [4] evaluated the effects of using 8%, 16%, and 24% blends of n-butanol with conventional diesel fuel. In this experiment, they implemented three different brake mean effective pressures in a high-speed direct injection diesel engine. Results of this study indicated that an increase of normal butanol volume would decrease CO and NO_x and increase the HC. Rakopoulos et al. [5] experimentally investigated the effect of 8% and 16% blends of n-butanol with conventional diesel fuel on performance and emissions of a six-cylinder,

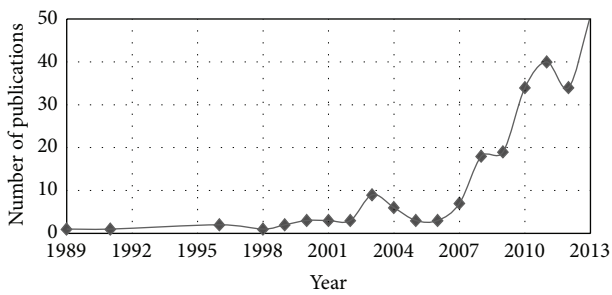

Figure 1: Number of studies related to butanol-diesel that were published between 1989 and 2013 (Scopus database).

water-cooled, turbocharged, and after-cooled heavy-duty direct injection Mercedes-Benz engine. Influence of diesel fuels with different amounts (0%, 5%, 10%, and 15% by volume) of n-butanol diesel fuel on the performance and emissions of a heavy-duty direct injection diesel engine with multi-injection capability was investigated by Yao et al. [6]. Their research demonstrated that with addition of n-butanol to diesel fuel, soot and CO emissions markedly decrease, whereas this blend fuel has a significant effect on break specific energy consumption and NO_x. Al-Hasan and Al-Momany [7] studied the effect of adding 10%, 20%, 30%, and 40% of isobutanol to diesel fuel on engine performance. They presented that effect of adding up to 30% of isobutanol with diesel fuel resulted in optimum engine performance, while 40% of isobutanol blend led to undesirable engine performance.

Karabektas and Hosoz [8] experimentally investigated the performance and emission of single cylinder direct injection diesel engine fueled with 5%, 10%, 15%, and 20% of isobutanol with diesel fuel. They found that with addition of isobutanol the brake specific fuel consumption and hydrocarbon increased, while CO and NO_x decreased. Asfar and Al-Rabadi [9] examined the effects of isobutanol blends with diesel fuel in a single cylinder water cooled four-stroke compression diesel engine on emission and soot. Their results indicated that soot, CO, NO_x, and unburned hydrocarbon decrease with addition of 5–10% isobutanol to diesel fuel. Ozsezen et al. [10] experimentally studied effects of isobutanol/diesel fuel blends on the performance and combustion characteristics of a heavy-duty diesel engine. The offered results showed that with the provided combined fuel, brake thermal efficiency, CO, and NO_x decreased. However, unburned hydrocarbon emission and brake specific fuel consumption were increased. Biao et al. [11] conducted an experimental study and reported that 30% butanol-diesel fuel considerably reduces the soot emission in high-speed heavy-duty diesel engine. However, the maximum of brake power and torque decreases from primary condition fueled with pure diesel fuel. Doğan [12] studies the influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions and presented that smoke, CO, and NO_x decrease and hydrocarbon increases with use of n-butanol/diesel fuel blends. Rakopoulos et al. [13] implemented normal butanol-low sulfur diesel blends at a single cylinder. Their results showed increment of ignition delay and fuel injection pressure, smoke, and decrement of CO and NO_x. Yao et al. [14] experimentally investigated the effect of exhaust gas recirculation on emission and performance of single four-cylinder diesel engine fueled by n-butanol/diesel fuel blends. Outcome of their test indicated that this blended fuel soot decreases and ignition delay increases.

The combustion effects of 80% butanol with 20% low sulfur diesel blend in two-stroke single cylinder were investigated by Tornatore et al. [15]. Yosimoto et al. [16] presented a study for investigating the effects of biomass n-butanol fuel blends with diesel fuel on emission and engine performance. They found that the break specific energy consumption of engine increases and that, like other studies, the smoke decreases. Lujaji et al. [17] examined the effects of fuel type such as croton oil, diesel fuel, and butanol blends on the emission, performance, and combustion properties of a turbocharged direct injection diesel engine. Zhang and Balasubramanian [18] found a particulate mass decrement in a study of 5%, 10%, 15%, and 20% of butanol blend with ultra-low-sulfur diesel in a nonroad diesel engine.

In addition to synthetic fuel strategy, the role of increasing injection pressure on engine emission and performance has become a considerable issue in recent years. Due to enhancement of the fuel-air mixing by high pressure injection, well-atomized fuel spray and more oxygen availability have increased.

While many experiments have been conducted to investigate the effects of high pressure injection on spray characteristics, computational fluid dynamics (CFD) methods, as an economic alternative for expensive experimental engine research, have been highly regarded. Development of the numerical codes and commercial software such KIVA, STAR-CD, and AVL FIRE for diesel engines research is one reason for this assertion. Additionally, development of open source CFD toolbox such as OpenFOAM to achieve the outlined purpose has also been considered.

There have been some authors who have implemented OpenFOAM for their investigation in this field. Gjesing et al. [19] presented a full 3D simulation of atomization, break-up, and in-flight spray phenomena based on an Eulerian-Lagrangian description by using OpenFOAM. Kassem et al. [20] explored the implementation of the eddy dissipation model through the new EdmFoam1.4 solver in OpenFOAM. Ismail et al. [21] numerically studied the influence of biodiesel-diesel fuel blends on emission characteristics of a light-duty diesel engine by using OpenFOAM.

As previously pointed out, major fuel for medium speed diesel engines such as heavy-duty maritime engines is HFO. Several studies dealing with usage of heavy fuel oil or diesel fuel effect on spray and combustion characteristics in marine diesel engine have been reported. Goldsworthy [24] presented a simplified model for vaporization and combustion of fuel as a mixture of residual base and cutter stock in marine diesel engines by using STAR-CD. Fink et al. [23] experimentally investigated the HFO, diesel fuel, and fuel-water emulsion effects on spray characteristics in medium speed marine diesel engine at 3 different high injection pressures. Kyriakides et al. [25] studied the influence of heavy fuel oil

Table 1: Comparison of physicochemical characteristics of butanol, methanol, and ethanol [1, 2].

Physicochemical properties	Butanol versus ethanol and methanol	Comparative advantage
Hydroscopicity	↓	Less affected by climate change
Flash point	↑	More safety compared to the other two types of alcohol
Energy density	↑	Producing about 25% more energy than methanol and ethanol
Cetane number	↑	Formation of a more uniformly combustion
Hydrocarbon chain	↑	Fairly nonpolar and more similarity to diesel fuels
Kinematic viscosity	↑	Viscosity of butanol is twice that of ethanol and five to seven times that of gasoline

↓ represents lower comparative value; ↑ represents higher comparative value.

properties on spray atomization by using KIVA CFD code. Struckmeier et al. [26] presented a multicomponent model for heavy fuel oil combustion by modifying the evaporation, ignition, and combustion models in KIVA-3V CFD code. Chryssakis et al. [27] offered physical model for HFO in large marine diesel engine for combustion modeling purposes. Herrmann et al. [28] presented a widespread simulation for suitable layout and dimensioning of the fundamental component in large two-stroke marine diesel engines by a test facility. Also, Herrmann et al. [29] experimentally studied spray and combustion processes at peripheral injection as a swirling flow in a constant volume chamber of large two-stroke marine diesel engines. For the same combustion chamber, Herrmann et al. [30] optimized injection and combustion of low quality heavy fuel oil in marine diesel engine. Andreadis et al. [31] numerically investigated effects of multiple fuel injection strategies on performance and emissions formation at full load in large two-stroke marine diesel engine by using KIVA CFD code. Stamoudis et al. [32] numerically investigated an evaporation model for two-component heavy fuel oil in constant volume chamber of marine diesel engines application.

It is quite evident from the presented literature review that spray characteristics have a fundamental role in improving the performance and efficiency of diesel engines. Spray penetration length, number of particles and their diameter, average particle velocity, and spray structure are some of these spray characteristics. On the other hand, the effect of fuel characteristics on spray fundamental parameters is undeniable. However, lack of in-depth study of HFO-butanol blends on spray characteristics at high pressure injection in marine diesel engines is fairly obvious from the cited research.

Therefore, in the present study, the influence of adding different volume fractions of n-butanol to HFO on liquid phase spray characteristics has been investigated. For this purpose, $C_{14}H_{30}$ as a reference HFO with five different percentage blends of n-butanol as fuel additives has been used. Furthermore, the present study has been conducted at two high injection pressures in medium speed diesel engines by using OpenFOAM CFD toolbox.

2. HFO/n-Butanol Blends in Diesel Engines

As stated earlier, some of the alternative fuels that are used instead of diesel fuel or blended with them are alcohol fuels such as ethanol, methanol, and butanol. However, butanol due to its physicochemical characteristics presented in Table 1 prevails in comparison with methanol or ethanol for blending with diesel fuel.

Table 2: Molecular structure of butanol isomers.

Isomers name		Molecular structure
Normal butanol	n-Butanol	$CH_3CH_2CH_2CH_2OH$
Secondary butanol	2-Butanol	$CH_3CH_2CHOHCH_3$
Isobutanol	i-Butanol	$(CH_3)_2CH_2CHOH$
tert-Butanol	t-Butanol	$(CH_3)_3COH$

As evident in Table 1, butanol as a biomass renewable fuel with high miscibility, when blended with diesel fuels, is considered a good choice compared to ethanol or methanol. Moreover, biofuels productions are economically justifiable. Hence, one of the only exciting paths to survive the current dependence of diesel engines upon oil products and to reduce emissions is moving toward the use of biofuels or combination of diesel fuels with biomass fuel such as butanol.

Butanol is an alcohol with 4-carbon molecular structure, which can be extracted by petrochemical process from oil or as a renewable fuel from biomass. This alcohol exits at 4 isomeric structures that is presented in Table 2. As observed, in accordance with the position of the hydroxyl group, different isomers arise, which, due to their similar formula, produce the same energy. However, different molecular structures yield different properties. Furthermore, mainly, normal butanol (n-butanol) is selected for blending with diesel fuels. This is because of the higher value of density, boiling point, and flash point of n-butanol compared with other isomers.

Additionally, as evident in Figure 2, n-butanol with straight linear hydrocarbon chain is more similar to hydrocarbon chain of $C_{14}H_{30}$ as a HFO. This similarity shows a high miscibility between n-butanol and $C_{14}H_{30}$.

Therefore, it seems like blend of $C_{14}H_{30}$ as a heavy fuel oil with n-butanol is an appropriate alternative fuel in medium speed diesel engines. Hence, a different percentage of n-butanol by volume blended in $C_{14}H_{30}$ is considered for the present study.

For numerical simulation of heavy fuel oil characteristics, $C_{14}H_{30}$ as a HFO model has been applied to OpenFOAM.

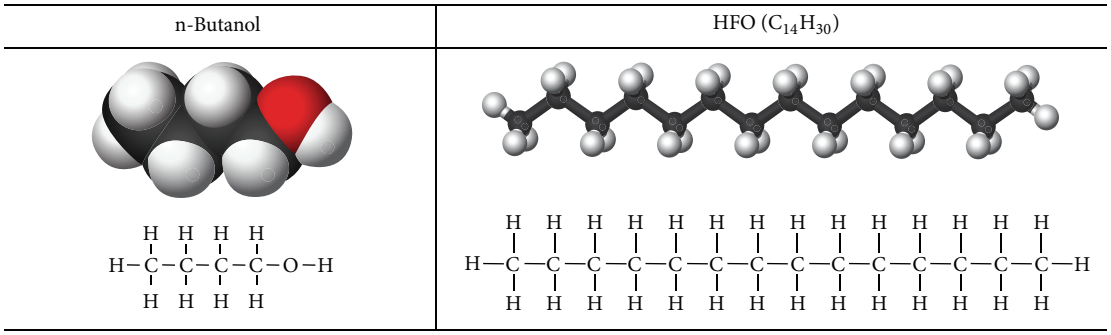

Figure 2: Molecular structure and sketch map of n-butanol compared with $C_{14}H_{30}$ as a heavy fuel oil.

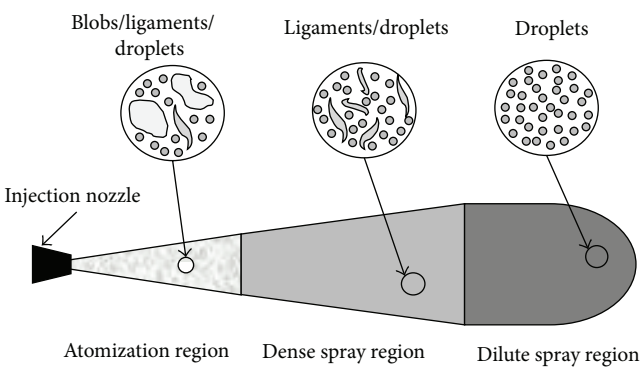

Figure 3: Schematic of liquid spray [22].

Table 3: Characteristics of the considered HFO and n-butanol.

Fuel properties	HFO	Normal butanol
Dynamic viscosity at 20°C (cP)	10.7	2.95
Density at 20°C (Kg m^{-3})	895	810
Surface tension (N m^{-1})	0.031	0.024

Accordingly, $C_{14}H_{30}$ thermophysical properties are implemented into Fuel Library in OpenFOAM. For this purpose, the NASA jannaf coefficient for thermophysical properties of C14H30 and n-butanol is calculated and applied to thermophysical properties. Fundamental characteristic of modeled heavy fuel oil and normal butanol is presented in Table 3.

Physical characteristics of the modeled heavy fuel and normal butanol, especially the dynamic viscosity, have a key role in the structure of spray formation and its fundamental properties. It must also be noted that these fuel physical characteristics are temperature dependent.

3. Technical Description of the Problem and Governing Equations

Two-phase liquid-gas spray and atomization phenomena are numerically investigated. Schematic form of liquid spray is presented in Figure 3. Liquid spray with its injection velocity penetrates into the gaseous surrounding of the combustion chamber. This gaseous environment is a combination of air and hot gases of combustion or recirculation gas, but, in this paper, pure air is considered as gaseous environment.

As evident in Figure 3, the first forming region after liquid fuel injection from nozzle into combustion chamber is atomization region. In this region, initially the liquid fuel core decomposes to blobs, ligaments, and droplets. These blobs as continuous liquid agglomeration have potential to become ligaments and similarly the ligaments have natural capabilities to break up to droplets. The liquid fuels spray transition from nozzle to the end of atomization region is known as a primary breakup. Study of primary breakup due to small dimension and high density of liquid core close to the nozzle is complicated at high injection pressure. So, in some approaches, because of unavoidable inaccuracies in the primary breakup model especially at high injection pressure, primary liquid core breakup is neglected. Moreover, injected droplets at atomization spray are directly considered as initial conditions for secondary breakups.

Next region is a dense spray area. The secondary breakup of drop and ligaments occurs in this region. There are no bulk liquid blobs, but ligaments as nonspherical liquid sheets are more numerous [22]. In other words, in this region the droplets resulting from atomization region disintegrate into smaller droplets. This phenomenon occurs due to droplets' interactions and aerodynamic influence of gas phase in combustion chamber.

There are several methods for modeling secondary breakup. However, in the present simulation, Reitz-Diwakar (RD) model is implemented which has been introduced by Reitz and Diwakar [34].

In dilute spray region without any ligament, there exist a large number of very small spherical droplets. However, it should be noted that spray body structure and its breakups are dependent upon the injector size, viscosity, and density of fuel and injection pressure differences [22].

Five partial differential equations represent the behavior of multiphase flow. These equations include conservation of mass, energy, and vectorial components of momentum along with considering a set of models to account for breakup and mass transfer as source terms. Additionally, Lagrangian particle tracking (LPT) approach is accounted for liquid droplet modeling in the present work. Conservation equation

of mass as a mathematical modeling of mass variation due to convection can be described by

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = S_{\text{ev}}. \quad (1)$$

As seen in this equation, a source term is added to the equation as contribution of the evaporation of fuel. Also, momentum conservation by considering all impressive parameters such as convection on momentum is obtained, using

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j - \tau_{ij}\right) = -\frac{\partial p}{\partial x_i} + S_{i,mo}. \quad (2)$$

Here, source term due to interaction with spray liquid phase is included. In addition, energy conservation is proportional to the following:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j h - \frac{\rho v}{\text{Pr}}\frac{\partial h}{\partial x_j}\right) = \frac{\partial p}{\partial t} + \frac{\partial p u_j}{\partial x_j} + S_{\text{he}}, \quad (3)$$

where a source term is the heat transferred from liquid phase. Moreover, Pr as a Prandtl number can be seen that indicates viscous diffusion rate divided by thermal diffusion rate.

Gas phase mainly contains air and vaporized fuel. This concept is given in a species conservation equation. Hence, in order to measure the mass fraction of fuel for each point of the gas phase, the following is employed:

$$\frac{\partial \rho X_f}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j X_f - \rho D \frac{\partial X_f}{\partial x_j}\right) = S_{\text{ev}}. \quad (4)$$

For considering LPT method, it should be noted that liquid phase is formed by disperse droplets of fuel. So, stochastic approaches in which droplets are considered discrete entities are feasible. The spray equation expresses conservation of probability in the condition space of randomized variables [35]. A probability conservation equation can be represented in the form of

$$\frac{\partial f}{\partial t} + \nabla_x \cdot (fu) + \nabla_v \cdot \left(f\frac{\partial u}{\partial t}\right) + \frac{\partial}{\partial r}\left(f\frac{\partial r}{\partial t}\right) + \frac{\partial}{\partial T}\left(f\frac{\partial T}{\partial t}\right) + \frac{\partial}{\partial y}\left(f\frac{\partial y}{\partial t}\right) + \frac{\partial}{\partial \dot{y}}\left(f\frac{\partial \dot{y}}{\partial t}\right) = \dot{f}_{\text{co}} + \dot{f}_{\text{br}}. \quad (5)$$

Here, $f(x, u, t, r, T, y, \dot{y})$ is a probable number of droplets per unit volume at a given position (x), given time (t), and radius ranging from r to $r + dr$, temperature and velocity, respectively, from T to $T + dT$, and from u to $u + du$, with droplet distortion parameters from y to $y + dy$ and until $\dot{y} + d\dot{y}$. There are also contributions by two sources due to the effects of collision and breakup of the droplets.

RANS formulation in OpenFOAM that is also known as Reynolds-averaged Navier-Stokes is implemented in this numerical study. Lower computational cost compared to LES and DNS is one of the RAS advantages [36]. For this purpose, a standard k-ϵ turbulence model is used for compressible fluid that has been considered.

Table 4: Model setup for combustion chamber parameter and injection parameters.

Model parameter		Value	Unit
Chamber parameters	Length	150	mm
	Diameter	50	mm
	Pressure	14	bar
	Temperature	298	K
Injection parameters	Nozzle diameter	0.27	mm
	Fuel injection pressure	600–1000	bar
	Initial temp. of fuel in injection	375	K
	Injection total mass	34	mg

On the other hand, chamber size and injection parameter from the work by Fink et al. [23] (as given in Table 4) have been applied to OpenFOAM. Based on Table 4, it can be seen that volume of the chamber is constant during the spray forming. Also, two high injection pressures are considered for investigating the effect of high injection pressure. In addition, initial temperature of injected fuel indicates that injection spray simulations are done at room temperature conditions. Therefore, a nonreacting and nonevaporating simulation of HFO/n-butanol blends spray has been implemented.

Properties of tested fuel blends including the n-butanol percentage and injection pressure are observed in Table 5.

As seen in Table 5, four different fuel blends are intended for this study. Hence, low volume fraction percentages of n-butanol up to the case of B20, as a high volume fraction percentage of n-butanol, are investigated for comparing against pure HFO (B0). Therefore, the proposed numerical scheme has the capability of investigating spray characteristics at different blends of HFO/n-butanol blends at two high injection pressures in marine diesel engine.

4. Results and Discussions

4.1. Mesh Resolution Sensitivity Analysis and Validation. Based on the literature review, there was no information available on nonreacting and nonevaporating HFO/n-butanol liquid-phase spray phenomenon or experimental data. Undoubtedly, adaptive mesh refining would be an interesting choice. For this purpose, mesh resolution study and numerical simulation of appropriate mesh with experimental data are investigated for HFO and butanol, separately.

Hence, mesh resolution sensitivity analyses on penetration length as a fundamental spray parameter for HFO were implemented as shown in Figure 4. These analyses are performed at injection pressure of 600 bar with several mesh sizes ranging from 0.004 m to 0.001 m in the Z-direction. Based on the results of Figure 4, an appropriate mesh is selected. Subsequently, by using the appropriate mesh, the computed result of spray length at injection pressure of 600 bar is compared against the experimental data of Fink et al. (2008) [23].

Table 5: Properties of tested fuel blends.

Case	Blend percentage by volume @ P_{inj} = 600 bar		Blend percentage by volume @ P_{inj} = 1000 bar	
	HFO	n-Butanol	HFO	n-Butanol
B0	100%	0%	100%	0%
B10	90%	10%	90%	10%
B15	85%	15%	85%	15%
B20	80%	20%	80%	20%

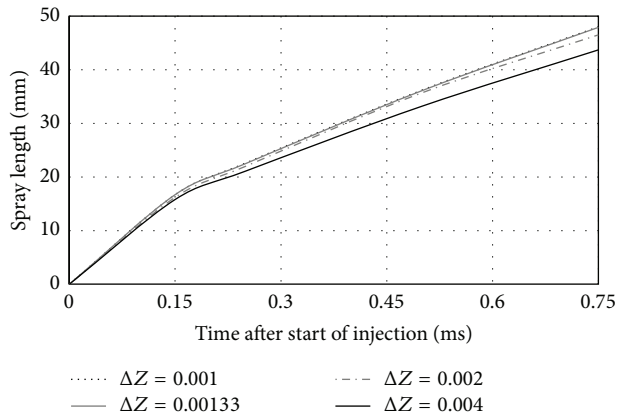

Figure 4: Mesh resolution sensitivity analyses of HFO spray length at injection pressure of 600 bar.

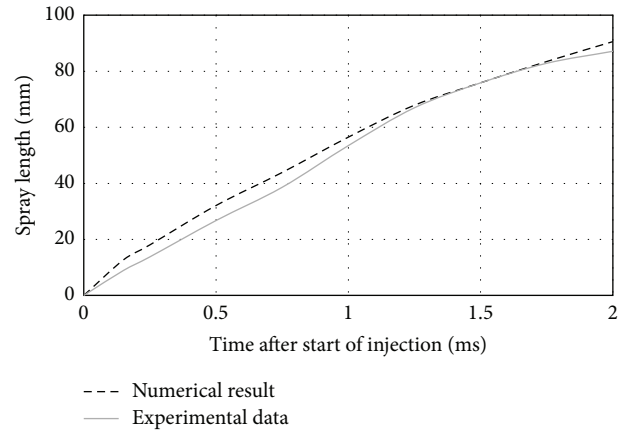

Figure 5: Comparison of numerical and experimental spray length of HFO at injection pressure of 600 bar [23].

Analyses of the results in Figures 4 and 5 indicate that 0.00133 m mesh size in Z-direction is matched with finer mesh. Additionally, with this appropriate mesh resolution, acceptable conformity between experimental results with numerical data is achieved. The RMSE of the results in injection pressure of 600 bar is 3.34.

Based on the described process, mesh sensitivity analysis and validation of appropriate mesh resolution at injection pressure of 1000 bar are presented in Figures 6 and 7.

Figure 7 reveals that there is an overprediction of the liquid length in the smallest mesh size. The RMSE at 0.00133 m mesh size as an appropriate mesh in injection pressure of 1000 bar is 3.36.

Therefore, appropriate mesh resolution for simulation of HFO spray injection at 600 and 1000 bar is obtained from Figures 4 to 7. Furthermore, relatively good agreement is achieved between numerical results and experimental data at both high injection pressures.

Mesh resolution sensitivity analyses of butanol and validation by the selected mesh resolution are provided in Figures 8 and 9. For this purpose, experimental data of Reddemann et al. [33] at injection pressure of 720 bar is considered. The RMSE of results at 0.00133 m as an appropriate mesh resolution is 1.09.

By the analyses of the obtained results of mesh resolution and validation, credibility in simulation of HFO spray injection and butanol at high injection pressure is established. Hence, proper convergence and valid solution of spray injection of the HFO/n-butanol at high injection pressure of 600–1000 bar can be expected. However, finer

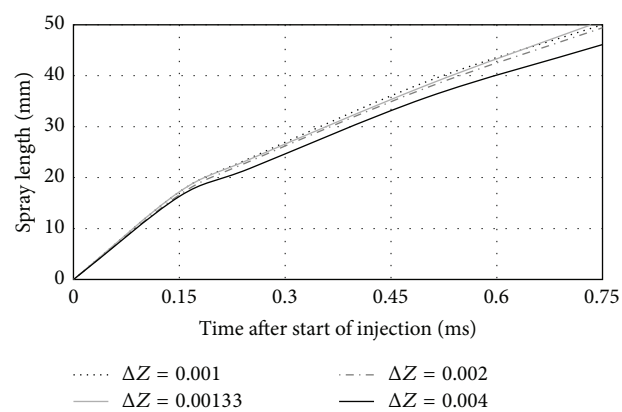

Figure 6: Resolution sensitivity analyses of HFO spray length at injection pressure of 1000 bar.

mesh resolutions ranging from 0.00133 m to 0.0008 m in Z-direction are implemented for blend of HFO and 5% of n-butanol at 600 bar according to Figure 10.

As seen in Figure 10, spray penetration length at higher mesh resolution has similar behavior with negligible difference with mesh size of 0.00133 m, as selected mesh resolution. Next, computed results of modeling different HFO/n-butanol blends are presented.

4.2. Analysis of Different HFO/n-Butanol Blends. One of the important influential factors on HFO/n-butanol spray length and structure of the spray is the increase in injection pressure.

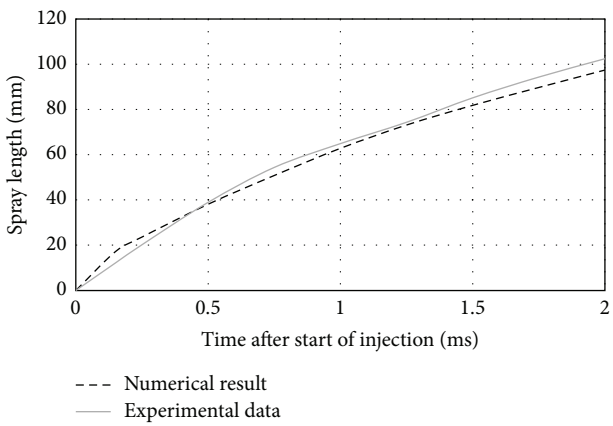

Figure 7: Comparison of numerical and experimental spray length of HFO at injection pressure of 1000 bar [23].

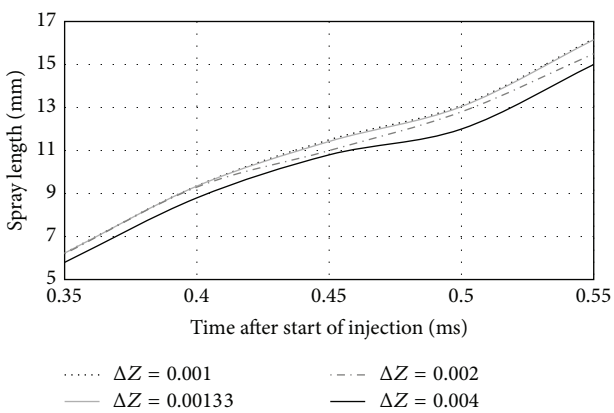

Figure 8: Resolution sensitivity analyses of butanol spray length at injection pressure of 720 bar.

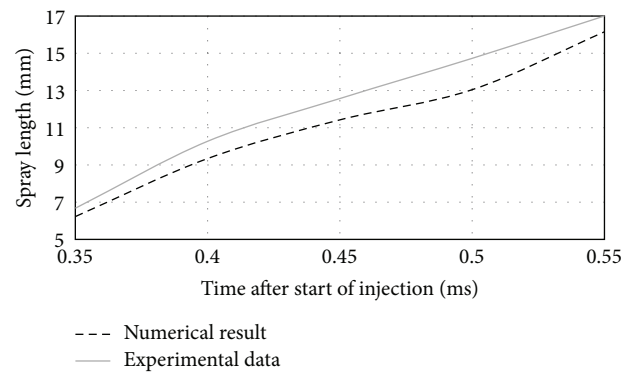

Figure 9: Comparison of numerical and experimental spray length of butanol at injection pressure of 720 bar [33].

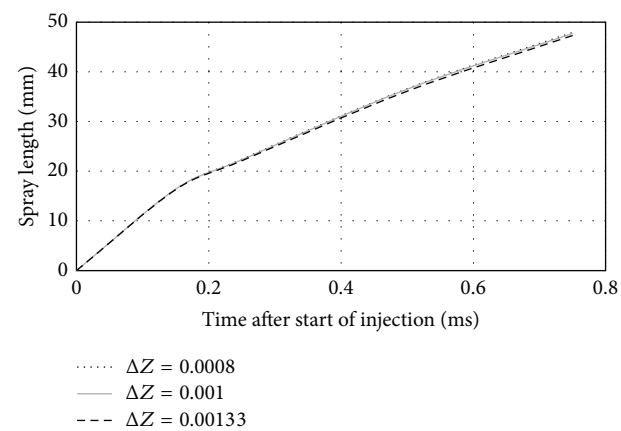

Figure 10: Resolution sensitivity analyses of B5 spray length at injection pressure of 600 bar.

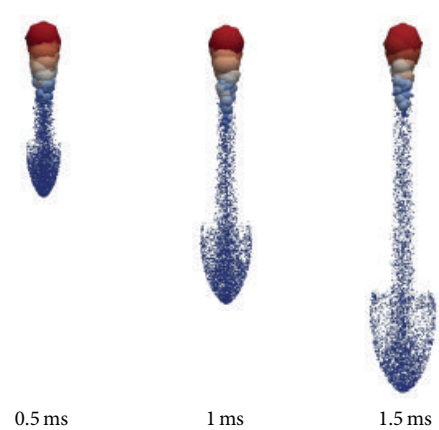

Figure 11: Time history of spray formation of B15 at injection pressure of 600 bar.

Time history of spray formation of B15 for the injection pressure of 600 bar can be seen in Figure 11.

As visible in Figure 11, when spray penetration length increases over time, tip of spray fuel jet expands in chamber due to growth of spray cone angle. Time history of spray formation for B15 at injection pressure of 1000 bar is presented in Figure 12. Based on these results, it can be concluded that with an increase in injection pressure, the growth rate of spray length and expansion of spray tip in timeline increase too.

Also, atomization, dense spray, and dilute spray regions in proportion of particles diameter to length of spray structure are evident in Figures 11 and 12.

Liquid phase spray length at different HFO/n-butanol blends at injection pressure of 600 bar and 1000 bar can be seen in Figures 13 and 14, respectively.

Based on Figures 13 and 14, it can be concluded that, when injection pressure increases from 600 to 1000 bar, the liquid phase spray of different HFO/n-butanol blends is increased with a similar trend. On the other hand, B10 has a higher spray length in timeline at the injection pressure of 600 bar. However, spray length of B20 is more than other fuel blends at injection pressure of 1000 bar. Nevertheless, the influence of different fuel blends on liquid spray lengths is considered negligible at both high injection pressures.

Particles volume in parcels at different HFO/n-butanol blends at injection pressure of 600 and 1000 bar is offered in Figures 15 and 16.

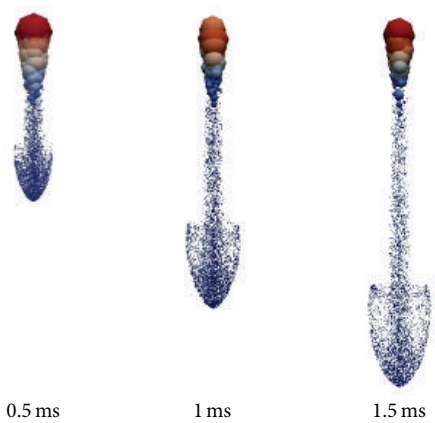

Figure 12: Time history of spray formation of B15 at injection pressure of 1000 bar.

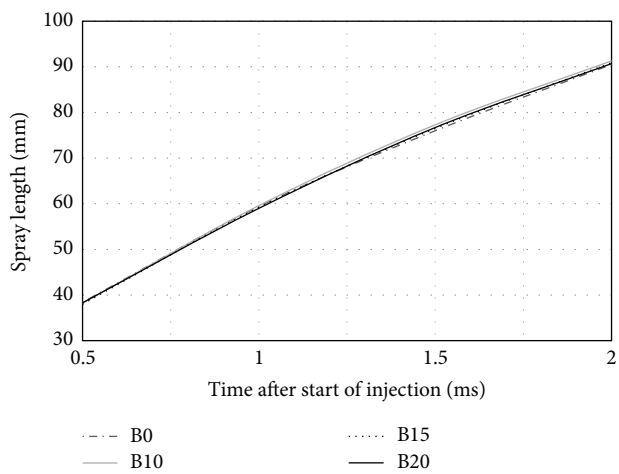

Figure 13: Liquid phase spray length of different HFO/n-butanol blends at injection pressure of 600 bar.

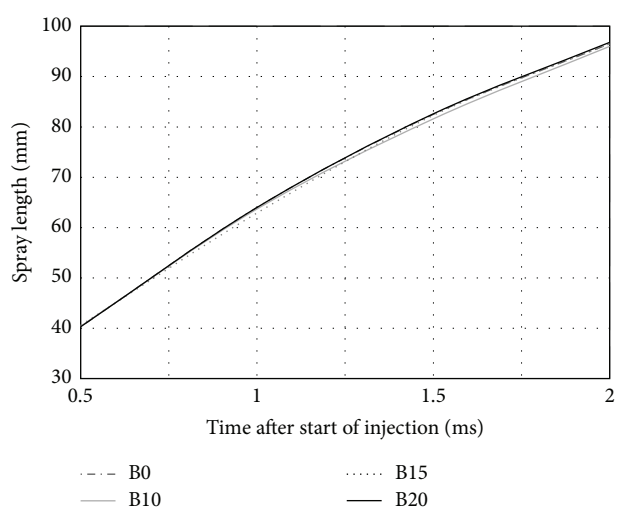

Figure 14: Liquid phase spray length of different HFO/n-butanol blends at injection pressure of 1000 bar.

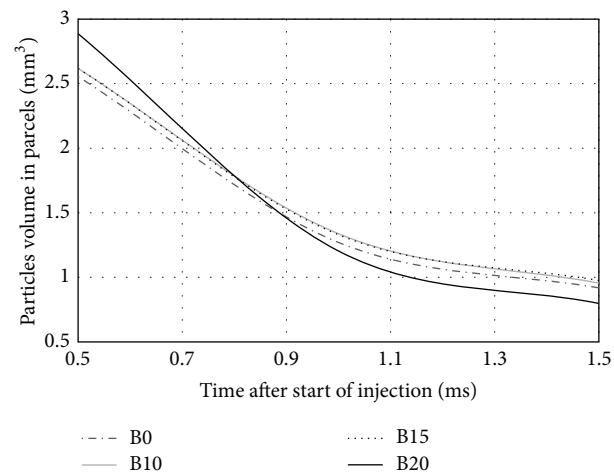

Figure 15: Particles volume in parcels at different HFO/n-butanol blends at injection pressure of 600 bar.

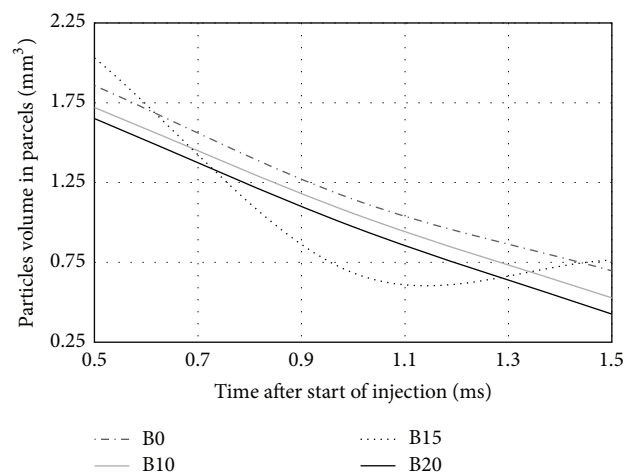

Figure 16: Particles volume in parcels at different HFO/n-butanol blends at injection pressure of 1000 bar.

Analyses of the results in Figures 15 and 16 indicate a decrease in particles volume in parcels in timeline at both high injection pressures. In other words, these results indicate that a reduction in droplet size due to the enhancement of atomization phenomena in progress of spray in timeline would cause a reduction of particles volume in parcels. However, it should be noted that the volume of spray in timeline, because of tip spray expansion, is clearly increased. As seen in Figure 15, particles volumes in parcels of B10 and B15 with higher approximation have the same value. Furthermore, addition of n-butanol to pure fuel leads to increase of particles volume in parcels for cases B10 and B15. In the meantime, B20 has an extreme change in particles volume in parcels rather than B0 in timeline. On the other hand, B0 has a maximum particles volume in parcels during timeline at injection pressure of 1000 bar. Moreover, the decrease in particles volume in parcels due to an increase of n-butanol additives is observed.

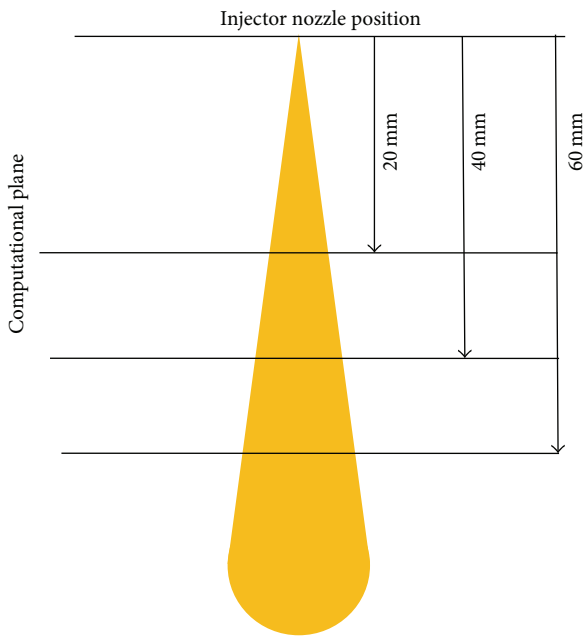

Figure 17: Computational planes located at 20, 40, and 60 mm from injector nozzle position in Z-direction.

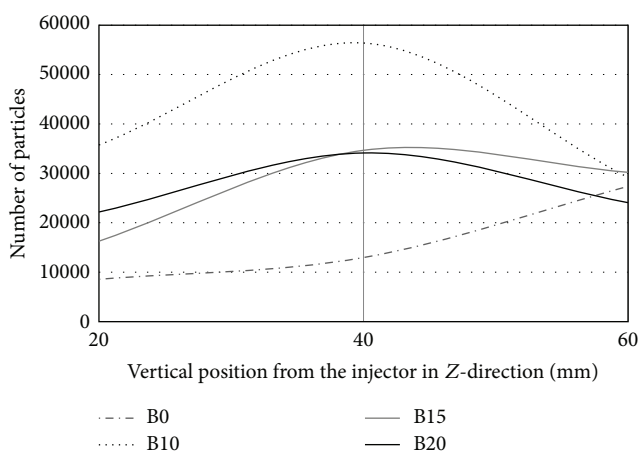

Figure 18: Number of spray particles for different HFO/n-butanol blends at injection pressure of 600 bar on different vertical positions from the injector.

Number of spray particles, average of particles diameter in parcels, and average velocity in Z-direction as a nonreactive injection spray analysis criteria on computational planes located at 20, 40, and 60 mm from injector nozzle position in Z-direction (as shown in Figure 17) have also been studied.

Computed values of the number of fuel spray particles for different HFO/n-butanol blends at computational horizontal planes from injector at injection pressure of 600 bar and 1000 bar can be seen, respectively, in Figures 18 and 19. By comparing the number of particles at different injection pressures, it is quite clear that the number of particles increases with an increase in the pressure. On the other hand, it can be concluded that higher breakup in atomization phenomenon

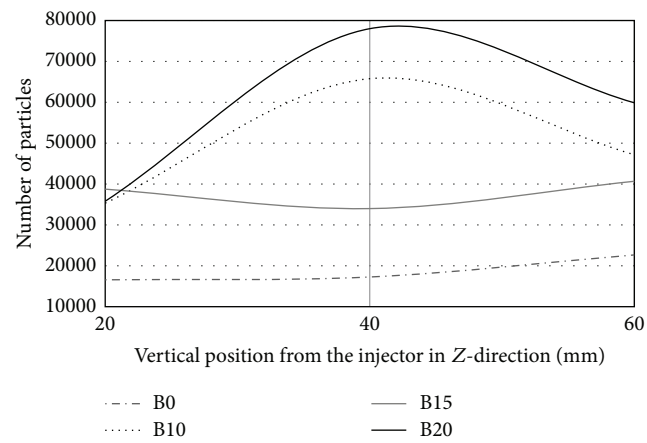

Figure 19: Number of spray particles for different HFO/n-butanol blends at injection pressure of 1000 bar on different vertical positions from the injector.

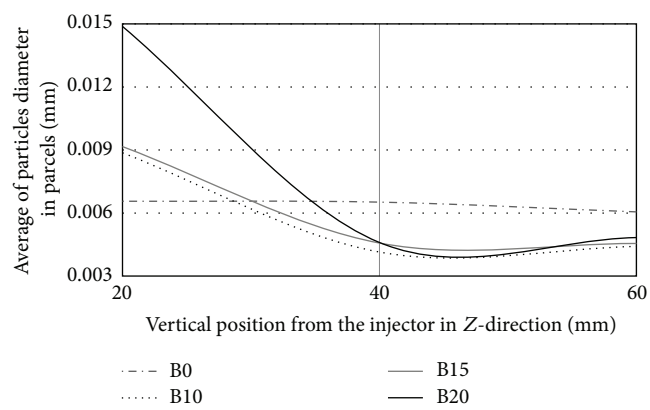

Figure 20: Average of particles diameter in parcels for different HFO/n-butanol blends at injection pressure of 600 bar on different vertical positions from the injector.

occurs due to higher pressure. Moreover, based on computed results in Figures 18 and 19, an increase in particles diameter with addition of n-butanol is evident. Also, B10 as lower quantity of n-butanol blend with HFO has higher number of particles at 600 bar. However, B15 compared with B20 has approximately the same value on different vertical positions from the injector. At the other extreme, numbers of particles increased with an increase in the amount of n-butanol in blended fuel at injection pressure of 1000 bar.

Average of particles diameter in parcels for different HFO/n-butanol blends at injection pressure of 600 and 1000 bar on the horizontal computational planes is shown in Figures 20 and 21. Based on these results, it is shown that an increase in injection pressure causes a decrease in average of the particles diameter in parcels. This observation is consistent with the fact that an increase in the number of particles by taking distance from the injector is due to the enhancement of atomization rate. However, as a result of a decrease in fuel particles, fuel cannot penetrate deeply into the chamber due to reduction of their inertia.

Table 6: Summary of the different fuel blends effects on the spray characteristics compared to pure HFO fuel.

Spray parameter	Different blended fuel @ P_{inj} = 600 bar			Different blended fuel @ P_{inj} = 1000 bar		
	B10	B15	B20	B10	B15	B20
Spray length	0.78%↑	0.11%↑	0.15%↑	0.56%↓	0.35%↓	0.14%↑
Particles volume in parcels	3.40%↑	3.65%↑	2.96%↑	11.97%↓	6.33%↓	21.32%↓
Number of particles	59.70%↑	39.76%↑	39.18%↑	61.88%↑	50.17%↑	67.46%↑
Average of particles diameter in parcels	9.81%↓	4.63%↓	21.29%↑	6.47%↓	37.37%↓	42.66%↓
Average velocity	17.81%↑	13.41%↑	18.04%↑	15.33%↑	8.02%↑	2.75%↑

↓ represents lower comparative value; ↑ represents higher comparative value.

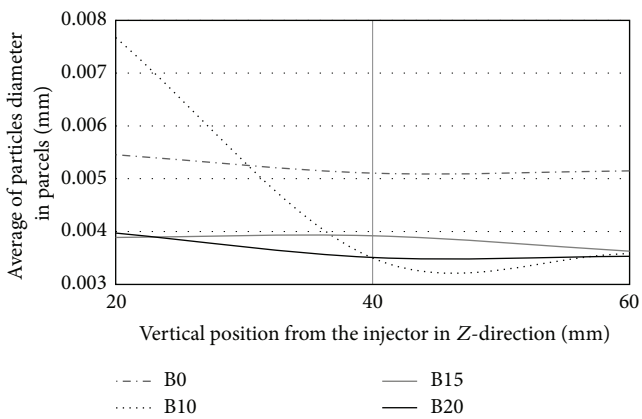

Figure 21: Average of particles diameter in parcels for different HFO/n-butanol blends at injection pressure of 1000 bar on different vertical positions from the injector.

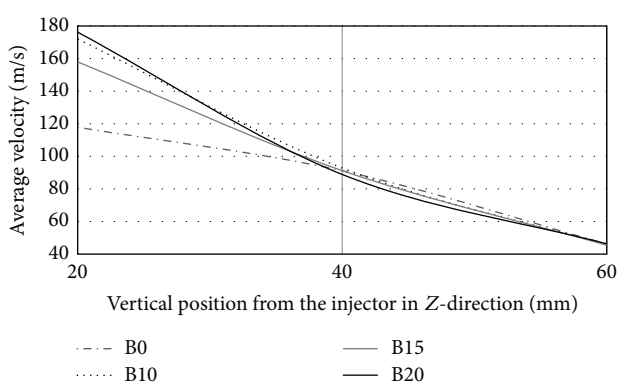

Figure 22: Average velocity in Z-direction for different HFO/n-butanol blends at injection pressure of 600 bar on different vertical positions from the injector.

Furthermore, the computed results indicate that average of particles diameter in parcels at a zone near the injector known as an atomization region increases by the rise of n-butanol to HFO at 600 bar. However, at dilute region, the HFO/n-butanol blends have lower average of particles diameter in parcels.

On the other hand, lower average of particles diameter in parcels of B15 and B20 compared with B0 can be seen through

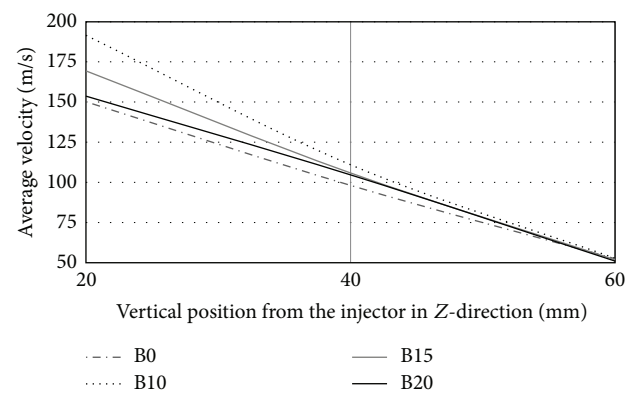

Figure 23: Average velocity in Z-direction for different HFO/n-butanol blends at injection pressure of 1000 bar on different vertical positions from the injector.

all different vertical positions from the injector at injection pressure of 1000 bar.

Computed values of the average velocity in Z-direction for different HFO/n-butanol blends on computational horizontal planes at injection pressure of 600 bar and 1000 can be seen in Figures 22 and 23. Comparison of the plots of different injection pressures in Figures 22 and 23 indicates that average velocity increases as the injection pressure increases. On the other hand, the addition of n-butanol to pure HFO causes an increase in average velocity through different vertical positions from the injector, especially at atomization zone near the injector. Moreover, B10 has a higher average velocity at both high injection pressures.

Therefore, it can be concluded from these results that higher injection pressure improves spray efficiency and performance. Also, relative average of influence of adding n-butanol to pure HFO fuel on the spray characteristics is summarized in Table 6.

5. Conclusions

In this paper, computational fluid dynamic simulation of nonevaporating and nonreacting of various HFO/n-butanol blends spray at high injection pressure has been performed. This was implemented in a constant volume chamber of medium speed diesel engine that has been implemented and

$C_{14}H_{30}$ heavy fuel oil with four different n-butanol blends that have been modeled.

Lagrangian particle tracking scheme was accomplished to conduct multiphase flow analyses by modified sprayFoam solver in OpenFOAM CFD toolbox. For this simulation, RANS equations with k-ϵ turbulence model have been solved for compressible fluid. Furthermore, Reitz-Diwakar model is employed for breakup simulation.

Spray pattern, liquid phase blended fuel spray length, particles volume in parcels, number of spray particles, average of particles diameter in parcels, and average velocity in Z-direction of the pure HFO and HFO/n-butanol blends have been studied at two different high injection pressures of 600 and 1000 bar.

OpenFOAM fuel library has been modified and further developed for applying the thermophysical properties of $C_{14}H_{30}$ and n-butanol. Main attention of the present study is the evaluation of n-butanol (0%, 10%, 15%, and 20%) blends HFO spray structure and fundamental spray parameter effects on the medium speed diesel engine injection efficiency at high injection pressures.

Grid independency analysis of HFO, n-butanol, and HFO/n-butanol has been conducted. The RMSE of the obtained liquid phase spray penetration length of HFO at the desired mesh resolution against the experimental data at pressure injection of 600 bar and 1000 bar are, respectively, 3.34 and 3.36. On the other hand, RMSE for butanol spray length at pressure injection of 720 bar is 1.09. Based on the good compliance of numerical result of HFO and butanol spray simulation compared with experimental data, it can be concluded that HFO/n-butanol blends simulations are valid. Among the important extracted results in this study are the following.

(1) Tip of spray fuel jet expansion through the penetration length progress at constant volume chamber can be concluded from time history of spray formation of B15. In particular, higher expansion is indicated at higher pressure injection.

(2) Computed spray formation for different blends of HFO/n-butanol shows that effects of n-butanol addition to pure HFO on spray length are negligible for both high injection pressures.

(3) Adding n-butanol to HFO increases the particles volume in parcels of spray at 600 bar by approximately 3%. However, HFO/n-butanol decreases the particles volume in parcels of spray compared to HFO at injection pressure of 1000 bar.

(4) HFO/n-butanol blends, especially B10, increase the number of particles of spray at both high injection pressures, significantly.

(5) All HFO/n-butanol blends except B20 at 600 bar decrease the average of particles diameter in parcels.

(6) HFO/n-butanol blends increase the average velocity of spray than pure HFO. This is particularly more evident at injection pressure of 600 bar.

Moreover, based on the numerical results presented in this paper, higher injection pressure improves spray efficiency and performance.

Nomenclature

HFO: Heavy fuel oil
NO_x: Nitrogen oxides
PM: Particulate matter
HC: Hydrocarbon
RAS: Reynolds averaged simulation
RANS: Reynolds averaged Navier-Stokes
RMSE: Root mean square error
CO: Carbon monoxide
S_{ev}: Contribution from the evaporation of fuel as a source term
$S_{i,mo}$: Interaction with the spray liquid phase as a source term
S_{he}: Heat that transfers from the liquid phase as a source term
Pr: Prandtl number
X_f: Mass fraction of fuel
LPT: Lagrangian particle tracking
$\dot{f}_{co}$: Contribution due to the effects of collision of the droplets
$\dot{f}_{br}$: Contribution due to the effects of droplets breakup
B0: n-Butanol (0% by volume), heavy fuel oil blend
B10: n-Butanol (10% by volume), heavy fuel oil blend
B15: n-Butanol (15% by volume), heavy fuel oil blend
B20: n-Butanol (20% by volume), heavy fuel oil blend.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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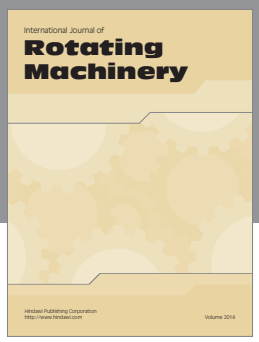
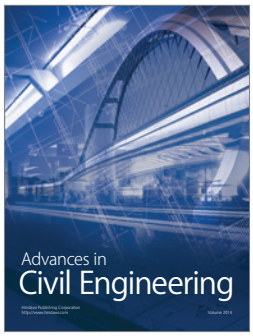
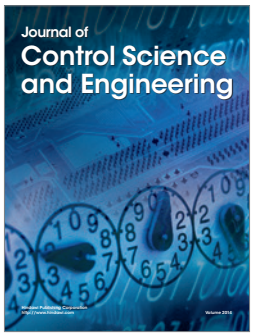
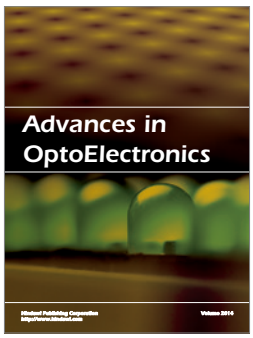
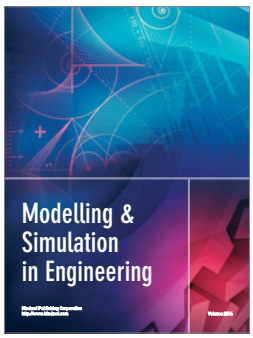
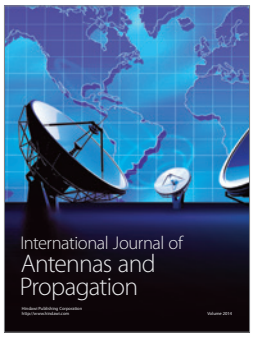
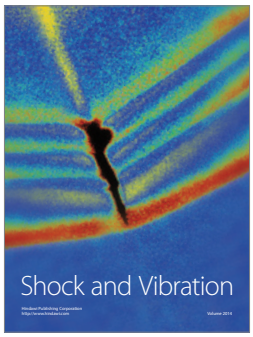
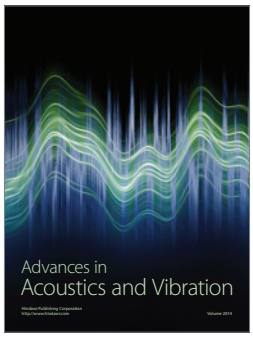






Hindawi

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