The Impact of Fuel Blends and Ambient Conditions on the Heating and Evaporation Of Diesel and Biodiesel Fuel Droplets

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THE IMPACT OF FUEL BLENDS AND AMBIENT CONDITIONS ON THE HEATING AND EVAPORATION OF DIESEL AND BIODIESEL FUEL DROPLETS

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ABSTRACT

This work presents recent approaches to the modelling of heating and evaporation of automotive fuel droplets with application to diesel-biodiesel fuel blends in conditions representative of internal combustion engines. The evolutions of droplet radii and surface temperatures for diesel-biodiesel fuel blends have been predicted using the Discrete Component model (DCM). These blends include up to 112 components (98 diesel hydrocarbons and up to 14 biodiesel components of waste cooking oil and soybean methyl esters). The effects of ambient conditions (ambient pressure and temperature, and radiative temperature) on multi-component fuel droplet heating and evaporation are investigated. Ambient pressures and temperatures, and radiative temperatures in the ranges 20-60 bar, 700-950 K, and 1000-2000k, respectively, are considered. Transient diffusion of 98 hydrocarbons and up to 14 methyl esters, temperature gradient, and recirculation inside droplets, are accounted for using the DCM. In contrast to previous studies, it is shown that droplet evaporation time and surface temperature predicted for 100% biodiesel (B100) are not always close to those predicted for pure diesel fuel (B0), but are dependent on the biodiesel fuel type and ambient conditions. Finally, the impact of radiation on opaque droplet lifetimes is shown to be significant, leading to about 19.4% and 23.3% faster evaporation for B0 and B100, respectively, compared to the case where radiation is ignored.

KEY WORDS: Biodiesel, Diesel, Droplet, Evaporation, Fuel blends, Radiation.

1. INTRODUCTION

The importance of modelling the heating and evaporation processes of multi-component fuel droplets has been highlighted in many studies (e.g. [1–4]). Understanding these processes is crucial to the design of internal combustion engines and to ensuring their good performance [5,6].

The interest in bio-fossil diesel fuel blends has been stimulated by the depletion of fossil fuels and the need to reduce carbon dioxide emissions that contribute towards climate change [7,8]. Also, compared to fossil fuels, biodiesel fuel has several advantages: it produces lower carbon dioxide emissions, has a higher flash point, higher lubricity, and is cost effective; in addition, blends of diesel-biodiesel fuels can be used in diesel engines with minimal/no modification [9,10]. Several suggestions have been made for modelling these processes (see [5,11]). The Discrete Component Model (DCM), suggested in [12] and validated against experimental data in [13], has been used in our analysis. This model is based on the analytical solutions to the heat transfer and species diffusion equations using the Effective Thermal Conductivity/Effective Diffusivity (ETC/ED) model [1,5,14]. This model is important because it takes into account the recirculation, temperature gradients and species diffusion inside droplets.

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Following [11,15–18], the analysis of droplet heating and evaporation processes is focused on blends of diesel-biodiesel fuel, and the effects of ambient conditions (pressure, ambient gas and radiative temperatures) on droplet lifetimes. Soybean Methyl Ester (SME) and Waste Cooking-Oil (WCO) are used to represent biodiesel fuels. Six fractions of diesel-biodiesel blends are investigated for the analysis of droplet heating and evaporation, using the DCM; these are B0 (100% diesel), B5 (5% biodiesel, 95% diesel), B20 (20% biodiesel, 80% diesel), B50 (50% biodiesel, 50% diesel), B80 (80% biodiesel, 20% diesel), and B100 (pure biodiesel) fuels.

2. MODEL

As in [15,19,20], our analysis is based on the previously developed model, which in turn is based on the analytical solutions to the heat transfer and species diffusion equations in droplets, assuming spherically symmetric processes. The effects of recirculation due to droplet relative motion in air are taken into account using the Effective Thermal Conductivity/Effective Diffusivity (ETC/ED) model. This approach has been validated in [12,21] for individual bi-component fuel droplets. The thermal radiation flux from a blackbody flame with an effective radiative temperature T_{rad} is accounted for. The droplet is assumed to be an opaque particle with emissivity equal to 1. The following boundary condition is applied at the surface of the droplet:

$$k_{\mathrm{eff}}\frac{\partial T}{\partial R}\bigg|_{R=R_{\mathrm{d}}} = \rho\,L\,\frac{\partial R_{\mathrm{d}}}{\partial t} + h\big(T_{\mathrm{g}}\text{-}T_s\big) + \sigma T_{\mathrm{rad}}^4,$$

(1)

where $k_{\mathrm{eff}} = \chi k_l$ is the effective thermal conductivity, k_l is the liquid thermal conductivity, χ is the recirculation coefficient, ρ is the liquid density, L is the latent heat of evaporation, $\frac{\partial R_{\mathrm{d}}}{\partial t}$ is the rate of droplet radius change due to evaporation, h is the convection heat transfer coefficient, T_g is the ambient temperature, and the Stefan-Boltzmann constant is $\sigma = 5.6703 10^{-8}$ W m^{-2} K^{-4}. The radiation flux emitted by the droplet σT_{d}^4 is negligible, compared with $\sigma T_{\mathrm{rad}}^4$. The effect of radiation is taken into account by replacing the gas temperature with the effective temperature $T_{\mathrm{eff}} = T_g + \frac{\rho L \frac{\partial R_{\mathrm{d}}}{\partial t}}{h} + \frac{\sigma T_{\mathrm{rad}}^4}{h}$.

Our approach describes the upper limit of the radiation heat transfer rate to the droplet. This approach is based on the estimation of the maximal possible, rather than actual, radiative absorption in droplets, which allows us to use a simplified model of the process. A more rigorous approach to modelling the radiative heating of semi-transparent droplets is described in [14]. The effect of radiative temperature on the heating and evaporation of a semi-transparent droplet (for example, see [22–24]) is expected to be less than on that of an opaque droplet. Similarly, semi-transparent droplet lifetimes are expected to be longer than those of opaque droplets. This is due to the fact that radiative absorption in semi-transparent droplets is less than that in opaque droplets.

The latent heat of evaporation (L) and saturated vapour pressure are calculated at droplet surface temperatures T_s; all other liquid thermodynamic and transport properties are calculated at the average temperature of the droplet. All gas properties in the vicinity of the droplet are calculated at the reference temperature ($T_{\mathrm{ref}} = \frac{2}{3}T_s + \frac{1}{3}T_g$). The analysis presented in this paper is based on the 1D numerical discretisation of the droplet volume into 300 concentric layers within the liquid phase. The time step is set to 10^{-6} seconds. For a full description of the numerical algorithm, and droplet volume discretisation procedures see [25]. The Effective Diffusivity (ED) model used in our analysis is described in [5].

3. RESULTS

The plots of droplet surface temperatures T_s and radii R_d versus time for various diesel-biodiesel fuel blends (B0 – B100), taking into account the contributions of up to 112 components in diesel-SME and diesel-WCO

fuels are shown in Figures 1 and 2, respectively. As in [17], the initial droplet radius is taken equal to $R_{do} =$ 12.66 μm, its axial velocity in still air and initial temperature are assumed equal to $U_d = 10$ ms^{-1} (assumed constant) and T_{do}=360 K, respectively; ambient air pressure and temperature are assumed constant and equal to p_g=30 bar and $T_g = 800$ K, respectively.
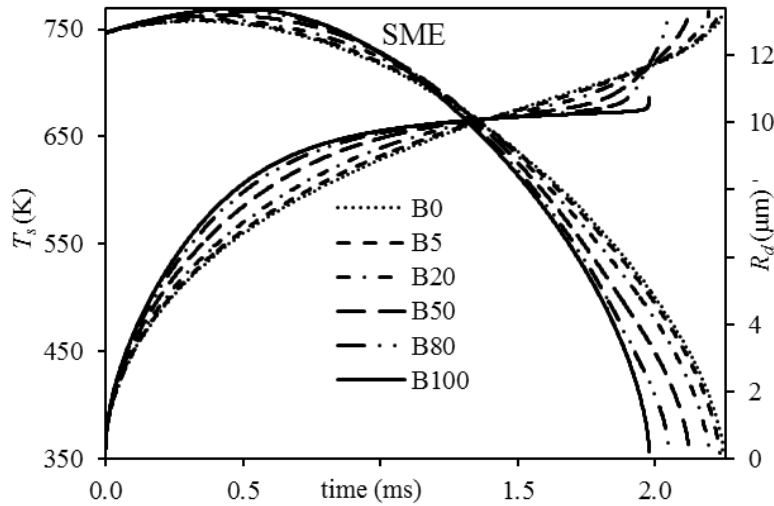

Fig. 1 Droplet surface temperature (T_s) and radii (R_d) versus time for various diesel-SME fuel blends.

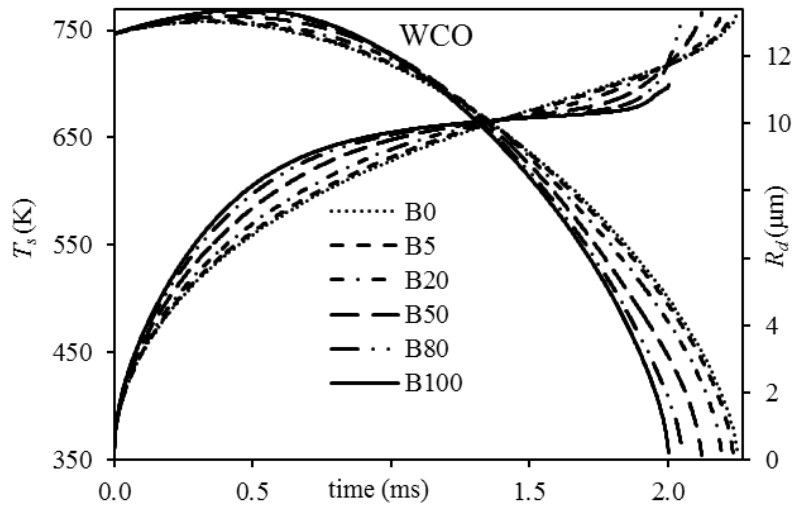**Fig. 2** Droplet surface temperature (T_s) and radii (R_d) versus time for various diesel-WCO fuel blends.

In Figures 1 and 2, one can see that increasing the fraction of biodiesel fuel from B5 to B100 has a noticeable effect on the evolution of T_s and R_d for both SME and WCO fuels. The predicted droplet surface temperature of B100 is higher than that of B5 during the initial heating period. This is attributed to a sudden increase in biodiesel fuel density, compared with a relatively small increase in diesel fuel density. According to [15], the increase in droplet surface temperature, due to the decrease in droplet surface tension, can enhance the droplet break-up process. The droplet lifetimes of SME and WCO biodiesel fuels blended with B0 fuel and their deviations from those predicted for B0 fuel (2.25ms) are presented in Table 1.

As can be seen from Table 1, the droplet lifetime for B100 (SME) fuel is 12% less than that for B0. This reduction does not exceed 0.7% for the B5 fuel blend for the same fuel. Also, the droplet lifetime of the WCO biodiesel fuel droplet is noticeably close to that of the B0 droplet; it is 12% and 0.7% shorter for the B100 and B5 blends, respectively. The deviation in droplet lifetimes for B100 of both SME and WCO cannot be ignored in most engineering applications; for B5 it can be tolerated in some engineering applications.

The difference in thermodynamic and transport properties between hydrocarbons and methyl esters is the main reason for the influence of biodiesel fuel fractions on the heating and evaporation of diesel fuel droplets. For instance, when increasing the biodiesel fractions, the droplet surface temperature tends to reach a plateau during the evaporation process, which is similar to the case predicted by the single component model (see [13,20]). Also, the significance of such behaviour depends on the input parameters and ambient conditions.

Table 1 Estimation of the droplet lifetimes of diesel-biodiesel fuel blends and their differences compared with B0 droplet lifetime (2.25 ms), $\left(\text{Diff}\% = \frac{\text{lifetime}_{B0} - \text{lifetime}_{blend}}{\text{lifetime}_{B0}}\right)$.

| Blends | Biodiesel Fuels | | | |
| | SME | | WCO | |
	Lifetime (ms)	Diff (%)	Lifetime (ms)	Diff (%)
B5	2.236	0.62	2.237	0.57
B20	2.198	2.31	2.194	2.49
B50	2.127	5.47	2.121	5.73
B80	2.055	8.67	2.052	8.80
B100	1.981	11.96	2.002	11.02

In contrast to [15,16,20], where the radiative effects on the evaporation of droplets are shown to be negligible, our analysis provides interesting updates to previous findings. In our model, the full composition of diesel-biodiesel fuel is considered, but with a simplified radiation model. The results of investigations under a range of diesel engine injection conditions, accounting for different radiation temperatures of B0 – B100 fuel blends, are presented in Figures 3 and 4, and Table 2.
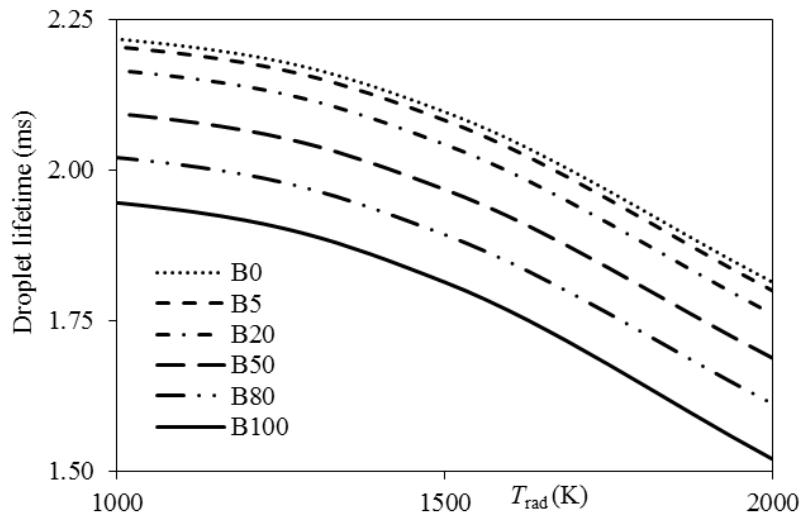

Fig. 3 The estimated droplet lifetimes versus radiation temperatures T_{rad} for B0 – B100 diesel-SME fuel blends.
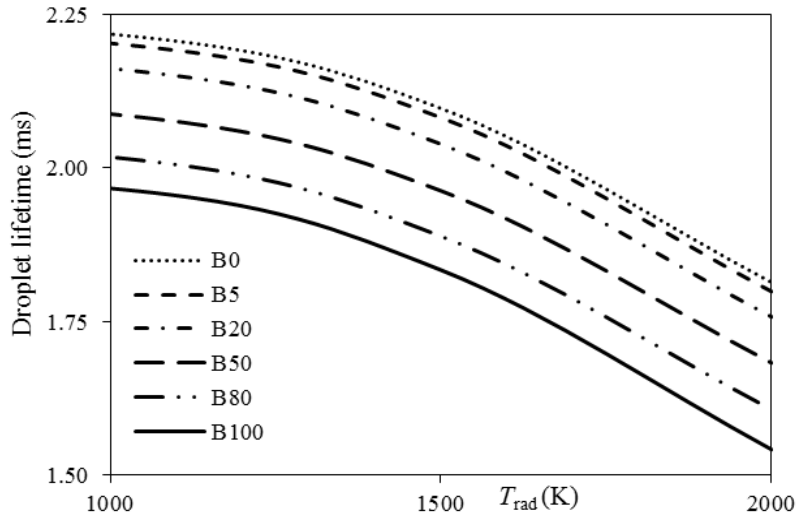
Fig. 4 The estimated droplet lifetimes versus radiation temperatures T_{rad} for B0 – B100 diesel-WCO fuel blends.

Table 2 The blended fuel droplet lifetimes under radiative effects and their estimated differences for the case when radiation is ignored, $\left(\text{Diff\%} = \frac{\text{lifetime}_{\text{no rad}} - \text{lifetime}_{\text{rad}}}{\text{lifetime}_{\text{no rad}}} \right)$.

	Blends	No radiation time (ms)	T_{rad}= 1000 K		T_{rad}= 1500 K		T_{rad} = 2000 K	
			time (ms)	Diff %	time (ms)	Diff %	time (ms)	Diff %
WCO	B0	2.250	2.218	1.42	2.097	6.80	1.814	19.38
	B5	2.237	2.203	1.52	2.082	6.93	1.799	19.54
	B20	2.198	2.162	1.64	2.039	7.23	1.758	20.02
	B50	2.127	2.091	1.70	1.963	7.71	1.683	20.87
	B80	2.052	2.016	1.75	1.889	7.94	1.607	21.69
	B100	2.002	1.964	1.89	1.834	8.40	1.542	22.97
SME	B0	2.250	2.218	1.42	2.097	6.80	1.814	19.38
	B5	2.236	2.204	1.43	2.083	6.84	1.800	19.50
	B20	2.198	2.166	1.46	2.043	7.05	1.761	19.88
	B50	2.127	2.094	1.55	1.968	7.48	1.688	20.64
	B80	2.055	2.021	1.65	1.893	7.88	1.612	21.56
	B100	1.981	1.946	1.77	1.814	8.43	1.520	23.27

As follows from Figures 3 and 4, the impact of radiation becomes more significant at high radiation temperatures. For instance, droplet lifetime is reduced by 19.4% and up to 23.3% for B0 and B100, respectively, when the radiation temperature is 2000 K. As follows from Table 2, the impact of radiative temperature on droplet lifetimes increases as the biodiesel fraction increases.

The effect of in-cylinder pressures and temperatures on the estimated droplet lifetimes for B0 – B100 fuel blends is presented in Figures 5-8. As follows from Figures 5 and 6, increasing ambient pressure at ambient temperature 800 K leads to a reduction in estimated droplet lifetimes with similar trends for all diesel-SME and diesel-WCO fuel blends. This effect is attributed to the fact that higher ambient pressure leads to increased gas density and a faster evaporation rate. Similar trends are observed for the impact of ambient temperatures on droplet lifetimes at ambient pressure $p_g = 30$ bar, as shown in Figures 7 and 8.
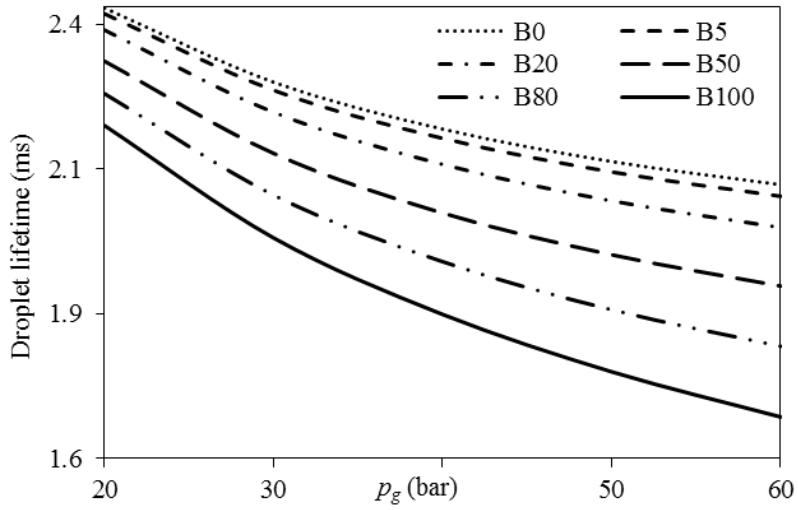
Fig. 5 The impact of ambient pressures on droplet lifetimes for B0 – B100 of diesel-SME fuel blends at T_g=800 K.
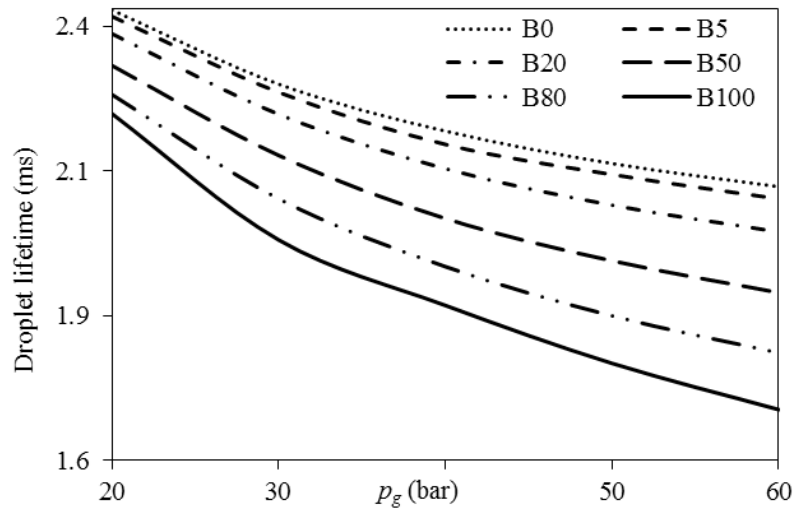

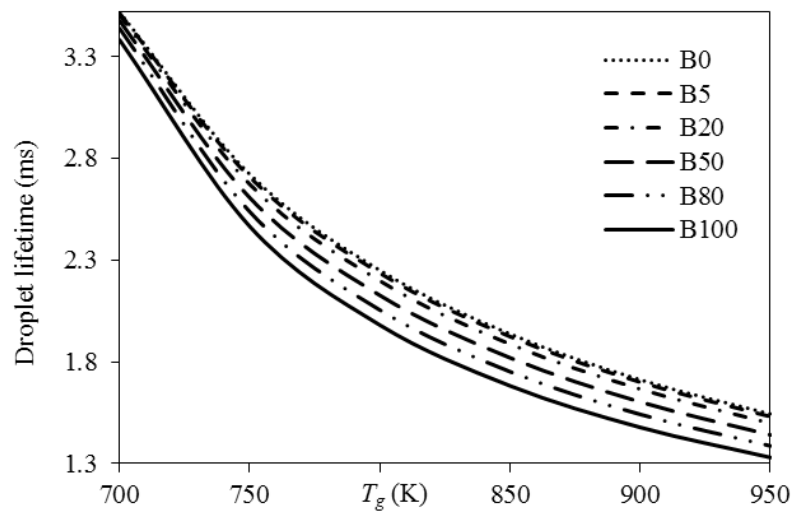**Fig. 6** The impact of ambient pressures on droplet lifetimes for B0 – B100 of diesel-WCO fuel blends at T_g=800 K.

Fig. 7 The impact of ambient temperatures on droplet lifetimes for B0 – B100 of diesel-SME fuel blends at p_g=30 bar.
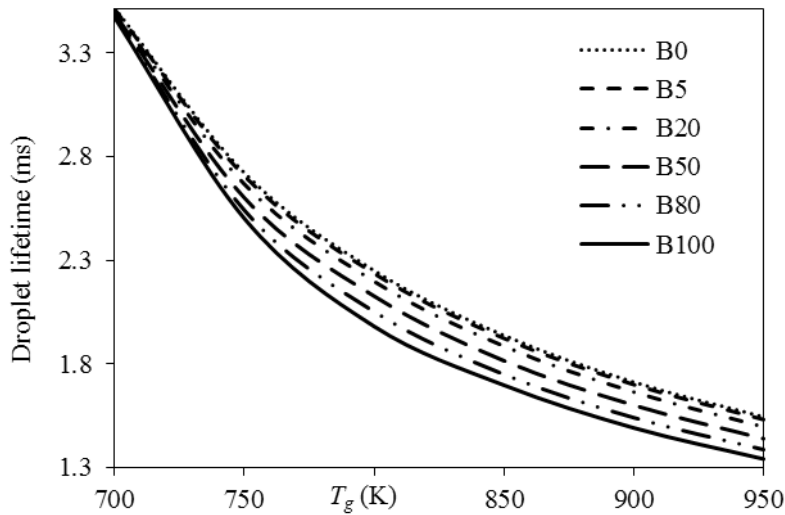
Fig. 8 The impact of ambient temperatures on droplet lifetimes for B0 – B100 of diesel-WCO fuel blends at p_g=30 bar.

As can be seen from Figures 7 and 8, ambient temperature has a noticeable impact on reducing droplet lifetimes for all diesel-biodiesel fuel blends. Increasing the ambient temperature leads to a reduction in the liquid density and an increase in the saturated pressure. Thus, the evaporation rate increases.

To summarise, increasing the radiative temperature, ambient pressure, or ambient temperature, leads to a faster evaporation of diesel-biodiesel fuel droplets, regardless of their blending fractions. The differences in droplet lifetimes for various diesel-biodiesel fractions are clearly observed for high ambient temperature and pressure. This can be attributed to different responses of the thermodynamic and transport properties of these fuels under these conditions.

4. CONCLUSIONS

The impact of ambient conditions, including pressures, temperatures, and radiative temperatures, and B0–B100 fuel blends on droplet heating and evaporation were investigated. The full compositions of diesel and biodiesel fuels, transient diffusion of species, recirculation, and temperature gradient inside droplets were accounted for, using the discrete component model. The analysis was focused on biodiesel (SME, WCO) and diesel fuel blends, B0, B5, B20, B50, B80 and B100.

It was shown that the droplet lifetimes for SME fuel were the smallest, followed by those for WCO fuel. The droplet lifetimes decreased with increasing biodiesel fractions, leading to a difference of 11.96% between B0 and B100 SME and 11.02% between B0 and B100 WCO results, under the same conditions. Also, the predicted B100 SME and WCO droplet surface temperatures were shown to be up to 10.5% and 8.8%, respectively, lower than those predicted for B0. It is concluded that increasing the radiative temperature, ambient pressure, and ambient temperature always leads to a faster evaporation of diesel-biodiesel fuel droplets.

ACKNOWLEDGMENTS

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