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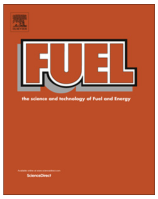

Full Length Article

Characteristics of non-evaporating, evaporating and burning sprays of hydrous ethanol diesel emulsified fuels

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ABSTRACT

Utilization of hydrous ethanol in diesel engines is beneficial not only for reducing the exhaust pollutant emissions but also for improving the lifecycle fuel efficiency including both in engines and refineries. However, so far detailed investigations on spray combustion characteristics of hydrous ethanol diesel emulsified fuels are rarely reported, though this information is crucial in combustion system design for better application of these fuels in diesel engines. In this paper, emulsions of the 20 wt% water-containing ethanol and commercial diesel fuel with volume fraction of the hydrous ethanol varied from 10 to 30% were firstly developed. Then, the physicochemical properties including the mixture stability, density, kinematic viscosity, surface tension, distillation temperature, latent heat of evaporation, etc. were investigated. Finally, the characteristics of non-evaporating, evaporating and burning sprays under the various injection and ambient conditions were clarified with the common-rail fuel injection system and the high-temperature, high-pressure, constant-volume combustion vessel. The results reveal that the difference of the spray cone angle and tip penetration length under either the non-evaporating or evaporating conditions for various fuels are relatively small, while the maximum liquid penetration length in the evaporating spray increases drastically with increased addition of the hydrous ethanol in the emulsions. In the case of burning spray, the natural luminosity of the flame decreases remarkably with the hydrous ethanol increasing, indicating the soot reduction in the flame. This effect becomes more pronounced with the ambient oxygen concentration decreasing. The mechanism of the above phenomena is discussed in depth.

1. Introduction

Bio-ethanol, as one of carbon neutral fuel and renewable energy, has been attracting worldwide attention for decades. Due to limitation of the total amount of bio-ethanol supply as a fuel, ethanol is mostly utilized by blending with fossil fuels. Owing to high hydrophilicity of ethanol, addition of surfactants is usually needed to obtain a stable blend of the low-carbon alcohol and fossil fuel, and even so existence of a little water in the blend may readily result in stratification of the blend. Therefore, highly purified ethanol is required to blend with fossil fuel to produce a stable mixture. Owing to the azeotropic property of ethanol and water, the processes of distillation and dehydration increase remarkably the energy consumption and cost of the ethanol production. For example, Shapouri et al. [1] reported that the energy consumption accounts for up to 37% in the total input energy and the net energy gain as fuel accounts only for 6% in the case of ethanol production with corn as feedstock. Flowers et al. [2] analyzed the energetic cost of ethanol distillation as a function of the final ethanol concentration with an assumption that the process starts with a 12% ethanol-in-water mixture produced by fermentation using the data in Ref. [3]. Their results showed that the energy required for distillation increases slowly at first, reaches 10% of the lower heating value at about 80% ethanol concentration, and then increases drastically with the ethanol concentration approaching the azeotrope at 95.6%. Recently, Saffy et al. [4] investigated the corn ethanol production with a range of ethanol concentrations from 58 wt% to 100 wt% to determine its impacts on energy use, water consumption and greenhouse gas (GHG) emissions in the refining stage of the corn lifecycle. They found that producing 86 wt% ethanol is optimal as thermal energy consumption decreases by 10%, suggesting the potential to reduce energy costs and refinery CO_2 emissions

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Nomenclature

$[O_2]_a$	ambient oxygen concentration [%]
ΔP	pressure difference across the injection hole [MPa]
ABE	acetone-butanol-ethanol
ASOI	after start of injection
C	model constant
CI	compression ignition
DISI	direct injection spark ignition
D_n	injector nozzle hole diameter [mm]
EBP	end boiling point [°C]
EGR	exhaust gas recirculation
fps	frame per second
GHG	greenhouse gas
HE	hydrous ethanol
HLB	Hydrophile-Lipophile Balance
h_{vap}	latent heat of vaporization
IBP	initial boiling point [°C]
IMEP	indicated mean effective pressure [MPa]
K	kelvin
K_{bt}	model constant
K_p	model constant
K_v	model constant
L	maximum liquid phase penetration length [m]
LTC	low temperature combustion
NO_x	nitrogen oxides
P_a	ambient pressure [MPa]
PDF	probability density function
P_{inj}	injection pressure [MPa]
RCCI	reactivity controlled compression ignition
RCEM	rapid compression expansion machine
S	spray tip penetration length [mm]
SI	spark ignition
SINL	spatially integrated natural luminosity
SOI	start of injection
t	time after start of injection [ms]
T_a	ambient temperature [K]
t_b	break-up time [ms]
T_f	fuel temperature [K]
U_{inj}	injection velocity [m/s]
W/O	water in oil
μ_a	kinematic viscosity of ambient gas [mm^2/s]
θ	spray cone angle [°]
ρ_a	density of ambient gas [kg/m^3]
ρ_f	density of fuel [kg/m^3]

by about 8%, respectively. Moreover, production of hydrous ethanol could lead to refinery water savings of between 3% and 6% at 86 wt% ethanol.

It is therefore clear that utilization of hydrous ethanol as a fuel may make the overall energy balance and production cost of bioethanol more attractive. Consequently, the number of researches with a focus on combustion of hydrous ethanol has been increasing in recent years. Breaux and Acharya [5] conducted the experimental study in a swirl-stabilized combustor for a gas turbine fueled with the hydrous ethanol ranging from 0 to 40% water by volume. They revealed that hydrous ethanol with up to 20% water contents can potentially be used in lieu of the more expensive anhydrous ethanol for combustion applications. Coronado et al. [6] investigated the flammability limits of hydrous and anhydrous ethanol at reduced pressures for aeronautical applications. Bradley et al. [7] studied the laminar mass burning and entrainment velocities as well as the flame instabilities of hydrous ethanol/air aerosols. Costa and Sodré [8] compared the performance and emissions from a production spark ignited (SI) engine fueled by the hydrous ethanol with 6.8% water content and the blend with 78% gasoline and 22% ethanol. They concluded that the use of hydrous ethanol leads to higher power at high engine speeds, while both fuels produced about the same power at low engine speeds, and that the hydrous ethanol produces higher thermal efficiency and specific fuel consumption than the gasoline-ethanol blend throughout all the engine speed range. Ambrós et al. [9] conducted numerical simulation along with the experiments to examine the effects of wet (hydrous) ethanol with 10%, 20%, 30 and 40% water contents in volume on the performance of a SI engine. They exhibited that while the gradual increase of specific fuel consumption is associated with the increasing water content, E70W30 (30% water-containing ethanol) shows the best performance, followed by the E80W20 (20% water-containing ethanol) blend; both are more efficient than the commercial pure ethanol. Lanzanova et al. [10] investigated the performance of a single cylinder direct injected spark ignition (DISI) engine fueled with gasoline, anhydrous ethanol and several wet ethanol of 5–20% water-in-ethanol volumetric content under stoichiometric and lean air/fuel ratios. They claimed that lower nitrogen oxides (NOx) emissions could be achieved with higher water-content ethanol at the expense of higher unburned hydrocarbon emission. Their analysis of wet ethanol energy production costs and engine operation conditions demonstrated that the lean engine operation with 10% water-in-ethanol fuel leads to global energy savings around 31% compared to anhydrous ethanol at stoichiometric conditions.

Compression ignited (CI) engines are usually more efficient than spark ignited (SI) reciprocating engines. Higher fuel conversion efficiency can be therefore expected for ethanol if it is burned in CI engines. Moreover, clean combustion in terms of reduced soot emissions can be achieved with addition of ethanol fuel into diesel engines (i.e. typical CI engine), owing to the properties of ethanol including oxygenated, low auto-ignitability and high volatility. Literatures with respect to ethanol as a fuel for diesel engines are voluminous, and most work deal with either the duel fuel mode with ethanol fumigation or direct injection of high purity ethanol blended with fossil or bio-diesel fuels. Readers may refer to the latest review papers [11,12] for more information, and only some examples are given here. Pedrozo et al. [13] examined the duel fuel combustion mode at 1200 rpm engine speed and 0.615 MPa indicated mean effective pressure (IMEP) on a heavy diesel engine with a target to improve combustion efficiency, maximize ethanol substitution as well as minimize NO_x and soot emissions. Jamuwa et al. [14] conducted the experimental investigation of performance, exhaust emissions and combustion parameters of stationary CI engine using ethanol fumigation in dual fuel mode. Asad et al. [15] proposed a Premixed Pilot Assisted Combustion (PPAC) strategy comprising of the port fuel injection of ethanol, ignited with a single diesel pilot injection near the top dead center to organize a low temperature combustion (LTC), and they demonstrated successfully ethanol–diesel PPAC up to a load of 18 bar IMEP with ultra-low NOx and soot emissions across the full load range. Rakopoulos et al. [16,17] studied the effect of ethanol-diesel blends on the performance and exhaust emissions of heavy duty DI diesel engine and demonstrated the potentials of ethanol addition on soot emission reduction. Park et al. [18] reported that the low and stable HC and CO emissions can be achieved through the application of narrow angle injector for the diesel–bioethanol blends combustion.