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Emission characteristics of methanol-in-canola oil emulsions in a combustion chamber

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HIGHLIGHTS

- Stable canola oil emulsions were made using Span 80, canola oil, and methanol.
- Emulsions produced lower NO_x, CO and unburned HC emissions than pure canola oil.
- Higher amount of methanol in the emulsions led to lesser NO_x, UHC and CO emissions.
- Increased vorticity at higher swirl angle led to better mixing and lower emissions.

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ABSTRACT

This paper focuses on the emulsification and combustion characteristics of different methanol-in-canola oil blends subject to different conditions including swirl number and equivalence ratio. Exhaust emissions data such as nitrogen oxides (NO_x), unburned hydrocarbons (UHC's), carbon monoxide (CO) and carbon dioxide (CO_2) emission levels were measured and analyzed thoroughly. Stable methanol-in-canola oil emulsions were made by using a combination of Span 80 and Tween 80 surfactants. The three different fuels studied were; pure canola oil, 89-9 emulsion [9% methanol – in – 89% canola oil emulsion with 2% surfactant (w/w)] and 85-12.5 emulsion [12.5% methanol – in – 85% canola oil emulsion with 2.5% surfactant (w/w)]. All the experiments were conducted in a 30 kW combustion chamber equipped with a twin fluid atomizer and a radial vane swirler. The swirler vanes were positioned at 60° and 51° angles (with respect to vertical axis) in order to achieve swirl numbers (SNs) of 1.40 and 1.0, respectively. The fuels were tested at equivalence ratios (ϕ) of 0.83, 0.91, 1.0, 1.05 and 1.11.

Ultimate analysis, higher heating value (HHV), kinematic viscosity and density were used to characterize the fuel properties. Experimental results showed that fuel type and swirl number had a major influence on emission levels. All the emulsions produced lower NO_x, CO and unburned hydrocarbon emissions than pure canola oil at both swirl numbers and all equivalence ratios. The emulsions also produced higher CO_2 emissions than pure canola oil. On comparing the performance of the emulsions, it was seen that the addition of methanol to the blend had a definite positive impact on the combustion characteristics. It was observed that higher percentage of methanol in the emulsions led to lesser NO_x, UHC and CO emissions. The vorticity imparted to the secondary air by the swirler also affected emission levels considerably. Increased vorticity at higher swirl angle led to better mixing of air and fuel, minimizing emission levels specifically at swirl number of 1.4.

1. Introduction

In the past decade, two important factors have influenced the world's energy market. First, a massive increase in the demand of conventional fossil fuels resulting in a rapid increase in their cost and the ever increasing difficulty being faced in finding and extracting more of these fuels from miles below the earth crust. Second, the concern for global warming and general health of population has led to stricter regulations on emissions of greenhouse gases like carbon dioxide (CO_2) and other major air pollutants like nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), soot and unburned hydrocarbons (UHC's). The above factors have motivated researchers to explore alternative energy sources like biofuels derived from agricultural products.

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Nomenclature

CC	combustion chamber
CO	carbon monoxide
CO_2	carbon dioxide
HHV	higher heating value
HLB	hydrophilic lipophilic balance
LPM	liters per minute
N_2O	nitrous oxide
NG	natural gas
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides (mainly a mixture of nitrogen oxide and nitrogen dioxide)
O_2	oxygen
ppmvd	parts per million by volume on a dry basis
ppmvdc	parts per million by volume on a dry basis corrected to 15% oxygen in the exhaust
R	inner radius of the outer annulus
R_h	outer radius of the inner annulus
SMD	Sauter mean diameter
SN	swirl number
SO_2	sulfur dioxide
SO_x	sulfur oxides
UHC	unburned hydrocarbons
v/v	volume basis
w/w	weight basis
X	desired HLB number
X_{NO}	measured/uncorrected NO mole fraction (ppmvd units)
$X_{NO,std}$	corrected NO mole fraction (ppmvdc units)
X_{O2}	measured oxygen mole fraction in the exhaust gas stream
$X_{O2,a}$	mole fraction of oxygen in ambient air, 0.21
$X_{O2,std}$	standard oxygen mole fraction, 0.15 (15% O_2 in the exhaust)
ϕ	equivalence ratio
d_0	Sauter mean diameter (μm)
U_R	relative velocity of primary combustion air to the velocity of the fuel
$A{:}F_{st}$	stoichiometric air to fuel ratio
Q_G	volumetric flow rate of the primary combustion air
Q_L	volumetric flow rate of the liquid fuel
V_G	velocity of primary combustion air
V_L	velocity of the liquid fuel
$U_{accuracy}$	uncertainty due to the accuracy of instrument
$U_{resolution}$	uncertainty due to the resolution of instrument
U_{total}	total uncertainty in the instrument
m_f	mass fraction of the liquid component in the emulsion
α	vane angle
μ_L	viscosity of liquid fuel (kg/ms)
μm	micrometer
ρ_L	density of liquid fuel (kg/m^3)
σ	surface tension of liquid fuel (kg/s^2)

Amongst the many available biofuels, biodiesel and ethanol are the most common and widely used liquid biofuels in diesel engines. Straight vegetable oils (SVO) are also quite promising alternative fuels as the energy characteristics of these oils are very close to that of fuel oil. The use of vegetable oils (VO) as fuels has been mainly in the form of biodiesel, blends with diesel or in their preheated refined form. However, very few studies involving the use of emulsified low grade alcohols in straight vegetable oils, as fuels for combustion have been published. Most of the published literature involves the use of emulsified fuels for compression ignition diesel engines. In the current experimental study, methanol was emulsified in pure canola oil in order to decrease the viscosity of canola oil and impart better flow properties to it at room temperature. The advantage of using methanol in canola oil emulsions (MCOE) is manifold. Firstly, canola oil is a sulfur free fuel and has very less nitrogen content. So, NO_x and SO_x formation should be greatly reduced due to the absence of fuel bound nitrogen and sulfur. Unlike conventional fossil fuels, the CO_2 produced during the combustion of canola oil is recycled during the cultivation of biomass and as such it is a CO_2 neutral fuel. Secondly, emulsions can be used to offset the amount of time and energy typically needed to produce suitable biodiesel fuels for use in boilers and engines. Economically, making vegetable oil (VO) based emulsions should be cheaper than making biodiesel because biodiesel production involves additional chemical processes after VO has been extracted from the crop. Thirdly, emulsions containing highly volatile micro-methanol droplets trapped inside less volatile canola oil should exhibit a micro-explosion effect during combustion. It has been reported that micro-explosions result in lower fuel emission [1]. Additionally, canola oil has negligible ash content indicating that it can be directly used in internal combustion engines. When used in boilers, it is almost a foul free fuel.

Many researchers [2–5] have performed combustion experiments of alcohol blended fuels in diesel engines and have found that NO_x emissions and exhaust smoke levels produced from alcohol blended fuels is lesser as compared to pure vegetable oil and diesel. The studies have also revealed that blended fuels lead to higher brake specific fuel consumption (BSFC) [2–5].

While there has been extensive literature on the use of alcohol blended fuels in I.C. engines, there are very few publications about the study of emulsified fuels for stationary burners. Research work done by Krumdieck and Daily [6] indicated that 10% ethanol addition to 90% pyrolysis oil (v/v) gave better atomization quality, improved the performance of the combustor and resulted in better flame stability. Mafra et al. [7] tested liquefied petroleum gas in a burner equipped with an adjustable swirler. From the experiments, the authors [7] concluded that the highest swirl number of 1.315 and the lowest fuel equivalence ratio of 0.61 gave minimal NO formation. Ishak and Jaafar [8] also ran combustion experiments with diesel fuel in a liquid fuel burner system having a radial swirler. A 26% reduction in NO_x emissions was achieved at 60° vane angle (SN = 1.427) compared to the 10° case. CO emissions were reduced by 48% for a vane angle of 70°.

Houlihan [1] has given a theoretical illustration about how emulsified fuel technology can deliver "the triple-crown" benefits including a reduction in NO_x and particulate matter, better fuel efficiency and a decrease in greenhouse gases, which is a difficult undertaking when dealing with most fossil fuels. Houlihan [1] claims that all the three benefits are due to the micro-explosion phenomena. Kadota and Yamasaki [9] have indicated that the occurrence of micro-explosions in the case of water-in-fuel emulsions gives researchers more design flexibility in the selection of fuel atomizing devices. Also, the reduction of flame temperature due to the amount of water present in the emulsions had a direct impact in decreasing thermal NO_x. Kitamura et al. [10] and Ferrante et al. [11] have been successful in detecting micro-explosions to a certain extent during the combustion of emulsified fuels.

The main objective of the current study is to understand the effect of equivalence ratio, swirl number and different methanol-in-canola oil emulsions on the emissions produced during their