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Modelling of spray evaporation and penetration for alternative fuels

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ABSTRACT

The focus of this work is on the modelling of evaporation and spray penetration for alternative fuels. The extension model approach is presented and validated for alternative fuels, namely, Kerosene (KE), Ethanol (ETH), Methanol (MTH), Microalgae biofuel (MA), Jatropha biofuel (JA), and Camelina biofuel (CA). The results for atomization and spray penetration are shown in a time variant condition. Comparisons have been made to visualize the transient behaviour of these fuels. The vapour pressure tendencies are revealed to have significant effects on the transient shape of the evaporation process. In a given time frame, ethanol fuel exhibits the highest evaporation rate and followed by methanol, other biofuels and kerosene. Ethanol also propagates the farthest distance and followed by methanol and kerosene. However, all biofuels have a shorter penetration length in the given time. These give penalty costs to biofuels emissions formation. The influences of initial conditions such as temperature and droplet velocity are also explored numerically. High initial temperature and velocity could accelerate evaporation rate. However, high initial temperature has resulted in low penetration length while high initial velocity produces contrasting results.

1. Introduction

Two separate important issues need to be addressed: (1) the environment crisis due to global warming and (2) the energy crisis that leads to the increase of global oil prices. Over time, the spike in global oil price will affect the domestic energy situation as well as impact the local society life [1]. International Energy Agency (IEA) has reported that the world will need 50% more energy in 2030 than it needs today [2], with the transportation sector becoming the second largest energy-consuming sector after the industrial sector. Nearly all fossil fuel energy consumption in the transportation sector is obtained from fossil fuels (more than 90%) with a small amount from natural gas and renewable energy sources [3,4]. However, as the demand for energy increases, the conventional oil and natural gas reserves that can be commercially exploited will diminish after approximately 41.8 and 60.3 years respectively [2].

Much effort has been employed to discover alternatives fuel sources which are sustainable, practical, nature friendly and reliable. These include the usage of biodiesel and biofuel. Biofuel is defined as a fuel comprised of mono-alkyl esters of long-chain fatty acids derived from renewable resources that can be produced by a simple chemical process known as transesterification. Transesterification is a process where the triglycerides react to alcohols in the presence of a catalyst [5] using edible, non-edible, waste vegetable oils and animal fats produced by organism [2,6,7]. Meanwhile, biodiesel (methyl or ethyl ester) is commonly used among biofuels which is considered as a very promising fuel in transportation. It possesses similar properties as diesel fuel and is miscible at any proportion of the fuel mixture [5] without producing any changes in the existing distribution infrastructure of the fuel [8]. Biodiesel is a non-toxic fuel that is ecological, uncontaminated and emits lesser pollutants. However, the main problem associated with the use of biodiesel is the high production cost (largely owing to the high cost of the feedstock). The use of biodiesel is steep and can be difficult due to its susceptibility to oxidation difficulties and poor low-temperature properties [8].

Despite that, increasing the thermal efficiency can optimize the combustion process and reduce the emission at the same time [9]. One of the methods is by spray characteristics. Spray behaviour is a critical factor in an engine performance [10] such as spray atomization and spray penetration. Spray atomization is a process which involves breaking-up the bulk of liquid jets into small droplets using atomizer or nozzles [9]. Meanwhile, spray penetration is defined as the propagation of droplet until it is fully vapourized. Liquid sprays are formed by discharging liquid at a high velocity from a nozzle. The use of spray is versatile as it can be used for agriculture, internal combustion engine and gas turbine

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Nomenclature

A	area (m^2)
CA	Camelina biofuel
c_d	drag coefficient
$c_{i,s}$	vapour concentration at droplet surface (mol/s m^2)
c_p	constant pressure specific heat (J/kg K)
$D_{i,m}$	diffusion coefficient of vapour in the bulk (m^2/s)
D_o	nozzle diameter (m)
d	diameter (m)
ETH	ethanol fuel
h	convective heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat (J/kg)
JA	Jatropha biofuel
KE	kerosene fuel
k_c	mass transfer coefficient (m/s)
k_∞	thermal conductivity of continuous phase (W/m K)
MA	microalgae biofuel
MMD	mass median diameter (m)
MTH	methanol fuel
MW	molecular weight (kg/mol)
m	mass (kg)
N_i	molar flux of vapour (mol/m^2 s)
Nu	Nusselt correlation
P	pressure (Pa)
P_{sat}	saturation vapour pressure (Pa)
Pr	Prandtl number of continuous phase
R	specific gas constant (J/kg K)
Re	Reynolds number
R_u	synthesized paraffinic kerosene (J/kmol K)
r	radius (m)
Sc	Schmidt number
SMD	Sauter mean diameter (m)
s	penetration distance (m)
T	temperature (K)
T_g	temperature of continuous phase (K)
t	time (s)
V	velocity (m/s)
α	volume fraction of droplet spray
θ	half angle of spray cone (°)
ρ	density (kg/m^3)
μ	molecular viscosity (kg/m s)
$\forall$	volume (m^3)

Subscript

P	droplet particle

combustors. Liquid that has a high discharge velocity will induce break-up streams to droplets and ensure enough inertial forces to transfer momentum, matter and heat effectively to the gas environment [11]. Spray zones can be classified into three zones; (1) at the nozzle tip where liquid discharge velocity is much larger than the stream velocity, (2) forced jet zone where the droplets' velocity decelerate and is comparable to stream's velocity, and (3) falling droplet zone where the droplets' velocity is lower than the terminal velocity [11,12].

2. Literature review

This section discussed on the overview of works which have been done that are related to spray behaviours. Chen et al. [10] have classified fuel spray behaviours into two categories: (1) macroscopic conditions and (2) microscopic conditions. They further added that macroscopic parameters include spray tip penetration and cone angle while the microscopic parameters are related to droplet velocity, droplet size and size distribution. From their macroscopic spray properties point of views, spray tip penetration is directly proportionate to the injection pressure, time duration and higher blend of biodiesel mixing ratio. However, higher blending ratio will result in a smaller cone angle, a small area and volume but higher velocity of spray. These lead to a reduction of quality in spray atomization. In contrary, spray tip penetration is inversely related to the ambient pressure. As the ambient pressure is increased, the spray cone angle will become larger. Furthermore, spray volume is increased as the injection pressure is increased until it reaches a certain limit.

Meanwhile, from microscopic spray properties point of view, the Sauter Mean Diameter (SMD) of the droplet is increased at a higher ambient pressure, radial and axial distance from the nozzle tip and at higher blending mixing ratio. However, a higher blend of mixing ratio will result in a more concentrated fuel distribution, larger droplet Mass Median Diameter (MMD) and span factor due to higher viscosity and surface tension. In contrary, higher injection pressure will reduce SMD but will increase the peak droplet's size volume frequency distribution. The reduction in droplet's diameter and the increase of the temperature of the surface were found to be strongly dependent on the fuel properties. For faster vapourization rate of the droplets, the fuel should have a combination of higher vapour pressure, lower latent heat thermochemical properties [13], low viscosity, low surface tension, low density [9] and low boiling point. They also added that pre-heating process could improve the vapourization performance of the SMD reduction.

Yule and Filipovic [14] have predicted the break-up length which refers to the distance of fully atomized droplet which is equivalent to 35% of the penetration length. Later, Ryu et al. [15] showed that the spray penetration length is directly proportional to the power of ¼ of back pressure. They also added that the spray impingements with ambient density have a greater influence on fuel evaporation and fuel mixture as compared to pressure and temperature intake condition. Concurrently, Chen et al. [10] included that the break-up length is increased with a larger diameter of nozzle but reduced at a higher injection pressure. For the time variant of spray penetration, Kostas et al. [16] found that spray tip penetration is proportional to the time power of 3/2 during the early stage until it reaches maximum velocity. However, they added that the spray tip velocity is found to be the square root of time at the same stage. Lee and Park [17] have studied both experiment and numerical analysis of fuel break-up using Kelvin-Helmhotz (KH) and Rayleigh–Taylor (RT) hybrid model in high-pressure diesel injection sprays. They discovered that KH breakup occurred near the injector while RT occurred at the secondary breakup and is distributed wider. For further improvement, Roisman et al. [18] have included the shock wave propagation in the air after the injection stage in their paper. Normal adiabatic shock wave has shown the impact to the tip velocity right after the injection stage.

Based on many numerical analysis and experimental works done by researchers to characterized micro and macroscopic droplet atomization and penetration process, rarely have been studied on different type of alternative fuels. This is equally important to underline the issue of environmental sustainability as well as to understand the behaviour of these alternative fuels. The main