International Journal of Heat and Mass Transfer 53 (2010) 3862–3873

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Infrared thermography and numerical study of vaporization characteristics of pure and blended bio-fuel droplets

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ARTICLE INFO

Article history:
Received in revised form 16 April 2010
Accepted 16 April 2010
Available online 1 June 2010

Keywords:
Multi-component droplets
Bio-fuel
IR thermography
Levitated droplet

ABSTRACT

The combustion dynamics and stability are dependent on the quality of mixing and vaporization of the liquid fuel in the pre-mixer. The vaporization characteristics of different blends of bio-fuel droplets injected into the air stream in the pre-mixer have been modeled. Two major alternate fuels analyzed are ethanol and Rapeseed Methyl Esters (RME). Ethanol is being used as a substitute of gasoline, while RME has been considered as an alternative for diesel. In the current work, the vaporization characteristics of a single droplet in a simple pre-mixer has been studied for pure ethanol and RME in a hot air jet at a temperature of 800 K. In addition, the behavior of the fuels when they are mixed with conventional fuels like gasoline and diesel is also studied. Temperature gradients and vaporization efficiency for different blends of bio-conventional fuel mixture are compared with one another. Smaller droplets vaporize faster than larger droplets ensuring homogenous mixture. The model was validated using an experiment involving convection heating of acoustically levitated fuel droplets and IR-thermography to visualize and quantify the vaporization characteristics of different bio-fuel blends downstream of the pre-mixer.

1. Introduction

Use of alternate fuels for power generation is considered to be one of the possible solutions to power crisis. Use of bio-fuels as alternate fuel helps the environment by reducing the fossil fuel usages and by conserving the agricultural activity where food production is being reduced. Many of the power generation industries have already taken steps in using renewable green energy. The aero-propulsion industry has already planned to switch to 50% bio-blended fuel before year 2011. However, there exists a strong disagreement among the researchers about the effects of these bio-blends on engine performances. This is principally due to the fact that the extraction process of bio-fuel from raw vegetable oil is still problematic [1].

The research efforts in the field of power energy generation showed that efficiency of the power generation unit depends very intimately on the fuel injection system. The working procedure of fuel injection system is based on the vaporization and dispersion characteristics of the liquid fuel. So, it is obvious that the efficient design of injection system for different bio-fuels for energy sector is dependent on the vaporization and dispersion processes of bio-fuels. In the Lean Premixed Pre-vaporized (LPP) combustion, a homogenous lean fuel–air mixture needs to be delivered to the primary zone, and combustion has to occur at lower temperatures with leaner equivalence ratios for reduced NO_x emission. Hence for bio-fuel, the delivery of homogeneous mixture of fuel and air is crucial which requires a clear understanding of the vaporization characteristics of the different blends.

In a standard power generation unit, fuel is generally injected into a hot stream of air in a mixing chamber prior to entering the combustor. The fuel is sprayed into the air stream in form of droplets. Injected droplets are entrained into the high temperature air stream which undergo evaporation resulting in droplet diameter reduction and rise in droplet temperature. The entrained droplet also is transported towards the combustor side situated downstream of the injector. The heat transfer from the hot air environment to the droplet is primarily through convection mechanism. The overall rate of evaporation and heat transfer depends on pressure and transport properties of the gas and the fuel. Depending on the droplet size, fuel properties and injector type, the injected droplets either get completely evaporated before reaching the combustor or it reaches the combustor in the form of smaller droplets dispersed in the air flow [2–4].

Droplet vaporization process has been modeled by several research groups particularly for a single droplet [5–13] and vaporizing turbulent sprays [14–16]. Maqua et al. [17] has reported experimental studies of the vaporization characteristics of monodisperse fuel droplets in airflow. They experimentally measured the droplet temperature using two-colour laser induced fluorescence thermometry. Similar experimental work on monodisperse ethanol droplets injected into the thermal boundary layer of a vertical heated plate has been done by Castanet et al. [18]. Maqua et al. [19] also reported a computational model of droplet

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doi:10.1016/j.ijheatmasstransfer.2010.05.003

Nomenclature

$B_{M\text{-}global}$	overall Spalding mass transfer number
B_T	Spalding heat transfer number
C_D	droplet drag coefficient
C_F	skin-friction coefficient
$D_{i\infty}$	mass diffusivity of vapor phase of ith species into air
h_{fg}	latent heat of vaporization of the liquid
Le_L	Lewis number of the liquid phase
$\dot{m}_i$	mass flow-rate of ith species at the droplet surface due to vaporization
$\dot{m}$	total mass flow-rate at the droplet surface due to vaporization
Nu_o	Nusselt number for a non-vaporizing sphere
Nu^*	Nusselt number corrected for surface blowing effect
Pe_L	Peclet number calculated based on liquid properties, $\mathrm{Pe}_L = \mathrm{Re}\cdot\mathrm{Pr}$
Pr	Prandtl Number
Q_L	heat transfer into the liquid
r	radial coordinate in the droplet calculations
r_o	initial droplet radius
r_s	instantaneous droplet radius
$\bar{r}_s$	non-dimensional droplet radius, $\bar{r}_s = r_s/r_o$
Re	Reynolds number of the droplet in the hot air
Sh_o	Sherwood number for a porous sphere
Sh^*	Sherwood number corrected for surface blowing effect
t	time
$\overline{T}$	non-dimensional temperature, $\overline{T} = (T - T_o)/T_o$
T_o	initial temperature of the droplet
T_s	droplet surface temperature
T_∞	air temperature at far field
U	droplet velocity in axial direction
U_s	velocity of the circulating liquid at the droplet surface
U_∞	air velocity at far field
V	droplet velocity in the traverse direction
V_r	radial component of the circulation velocity
$\overline{V}_r$	non-dimensional radial component of the circulation velocity, $\overline{V}_r = V_r/U_s$
V_θ	angular component of the circulation velocity
$\overline{V}_\theta$	non-dimensional angular component of the circulation velocity, $\overline{V}_\theta = V_\theta/U_s$
α_L	thermal diffusivity of the liquid phase
β	non-dimensional surface regression rate parameter, $\beta = 1/2(\partial\bar{r}_s/\partial\tau)$
$\chi_{v,s}$	mass fraction of the vapor phase at the droplet surface
$\chi_{v,\infty}$	mass fraction of the vapor phase at far field
χ_i	mass fraction of ith species
$\bar{\chi}_i$	normalized mass fraction for ith species, $\bar{\chi}_i = (\chi_i - \chi_{i,o})/\chi_{i,o}$
$\chi_{i,o}$	initial mass fraction of ith species
η	non-dimensional radial coordinate, $\eta = r/r_s$
μ_g	average dynamic viscosity of air field
μ_L	dynamic viscosity of the liquid phase
θ	angular coordinate in the droplet calculations
ρ_s	density of the vapor phase
ρ_L	density of the liquid phase
ρ_∞	air density at far field
τ	non-dimensional time, $\tau = \alpha_L \cdot t/r_o^2$

evaporation comprising of two vaporizing species. However, no researcher has studied the vaporization characteristics and flow dynamics of different bio-fuel blends.

In this work, a numerical model has been developed to predict the vaporization characteristics of a bio-fuel droplet in a hot air stream along with a detailed experimental analysis and validation for a levitated single droplet. Different types of fuels and fuel blends have been used to study the effect of droplet size and fuel type on the vaporization pattern. Furthermore, experiments involving IR-thermography of a convectively heated droplet in a levitator have been done to validate the model.

2. Computational model

In the current model, a single droplet has been considered. The effect of shape deformation due to aerodynamic force has been neglected. The heat transfer between the droplet and the air stream has been modeled by solving the energy equation. The diffusion and evaporation of different species within the droplet has been modeled by adopting the approach outlined by Sirignano [20]. There are three distinct parts in the model. The first part looks into instantaneous droplet velocity and displacement. The effect of the gravitation field has been neglected in this model. The air stream velocity is considered to be axial.

$$\frac{\partial U}{\partial t} = \frac{3C_D}{8r_s}\frac{\rho_\infty}{\rho_L}|U_\infty - U|(U_\infty - U) \tag{1}$$

$$\frac{\partial V}{\partial t} = -\frac{3C_D}{8r_s}\frac{\rho_\infty}{\rho_L}V^2 \tag{2}$$

$$\frac{\partial r_s}{\partial t} = -\frac{\dot{m}}{4\pi\rho_L r_s^2} \tag{3}$$

The drag coefficient C_D is defined by the correlation suggested in Ref. [21].

$$C_D = \frac{24}{\mathrm{Re}(1 + B_{M\text{-}global})} \tag{4}$$

Reynolds number is defined as, $\mathrm{Re} = \frac{2\rho_\infty r_s\sqrt{(U-U_\infty)^2+V^2}}{\mu_g}$. But the Spalding mass transfer number, B_M is dependent on vaporization rate of different species. Also the properties like, viscosity μ_g depends on the average film temperature which is defined as $T_{\mathrm{film}} = (2T_s + T_\infty)/3$ [22]. The unknowns, film temperature and vaporization rates are calculated from the liquid phase analysis. Solution of the aforementioned Eqs. (1)–(3) will be used to compute the trajectory of the droplet and the diameter reduction within the air flow field.

The vapor phase solution surrounding the droplet is obtained considering a quasi-static analysis [20]. It can be justified by lower thermal diffusivity of liquid phase, which results in higher relaxation time. Clift et al. [23] suggested correlations for non-vaporizing spheres following this assumption.

$$\mathrm{Nu}_o = 1 + (1 + \mathrm{Re}\cdot\mathrm{Pr})^{1/3}\cdot f(\mathrm{Re}) \tag{5}$$

$$\mathrm{Sh}_o = 1 + (1 + \mathrm{Re}\cdot\mathrm{Sc})^{1/3}\cdot f(\mathrm{Re}) \tag{6}$$

The function $f(\mathrm{Re})$ in these equations is given by

$$\begin{aligned} f(\mathrm{Re}) &= 1, \quad \mathrm{Re} \leqslant 1 \\ f(\mathrm{Re}) &= \mathrm{Re}^{0.077}, \quad 1 \leqslant \mathrm{Re} \leqslant 400 \end{aligned} \tag{7}$$

Due to surface blowing effect, the heat and mass transfer from the droplet surface will be affected, which can be taken care of by introducing corrected Nusselt and Sherwood number [20].

$$\mathrm{Nu}^* = 2 + \frac{\mathrm{Nu}_o - 2}{F(B_T)} \tag{8}$$

$$\mathrm{Sh}^* = 2 + \frac{\mathrm{Sh}_o - 2}{F(B_{M\text{-}global})} \tag{9}$$